THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine
Committee on Systems Integration for Project Constellation
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences

500 Fifth Street, NW, Room 1002A
Washington, DC 20001
Phone: 202-334-2858
Fax: 202-334 2482
E-mail: aseb@nas.edu
www.national-academies.org/aseb

September 21, 2004

Rear Admiral Craig E. Steidle, USN (Ret.)
Associate Administrator for Exploration Systems
NASA Headquarters
300 E Street SW
Washington, DC 20546
Subject: Systems Integration for Project Constellation

Dear RADM Steidle:

At your request, the National Research Council recently established the Committee on Systems Integration for Project Constellation. As specified in the statement of task (see Attachment A), the committee assessed the relative merits of four major systems integration approaches that Project Constellation could use to move forward with human exploration of the solar system, beginning with a return to the Moon. The four approaches are as follows:

- government serving as the systems integrator
- one of Project Constellation's major hardware prime contractors serving as the systems integrator
- an existing company (but not one of the Project Constellation prime contractors) serving as the systems integrator
- a new company created by the government serving as the systems integrator

To conduct the assessment the committee first developed a working definition of (1) the scope of Project Constellation, (2) the scope of the Project Constellation systems integration task, (3) the relevant criteria for use in making the committee's assessment, and (4) surrogate organizations that the committee used for assessing the systems integration approaches listed above.

In view of the short study schedule and the nature of the task, this report does not include extensive references or rely on detailed evidence from outside sources to support the assessments. Rather, it relies primarily on the consensus views and judgments of the committee members, based on their substantial project and program management experience (see Attachment B). To guarantee a breadth of perspectives, a large committee of senior executives, engineers, and researchers with extensive and diverse experience in industry, government, and academia was appointed. Some of this experience was shared in the form of five presentations made by committee members on systems integration lessons learned from space and nonspace megaprograms that exhibited systems integration characteristics comparable to those of Project Constellation in terms of scope and complexity (see Attachment C).

The in-depth overview of Project Constellation that you presented to the committee and other background information provided previously established the framework for the committee's further evaluation of the systems integration task.[1] In addition, the committee received an overview of the report of the President's Commission on Implementation of U.S. Space Exploration Policy from Gen. Lester Lyles, a member of both this committee and the President's Commission.[2] The President's Commission was created to examine and make recommendations on implementing the vision for space exploration. The National Aeronautics and Space Administration (NASA) created Project Constellation to implement this vision.

A detailed list of typical systems integration tasks appears in Attachment D. The results of the committee's deliberations on the optional tasks from the statement of task are described in Attachment E. Report reviewers are acknowledged in Attachment F.

PROJECT CONSTELLATION DEFINED

NASA's Office of Exploration Systems is implementing Project Constellation with a system-of-systems approach that encompasses all of the systems—to include vehicles, equipment, processes, tools, facilities, staffing requirements, and others—necessary for human exploration of the solar system. This includes robotic precursor missions to prepare the way for human exploration; crew transportation systems—particularly development of a new crew exploration vehicle (CEV)—and the selection of a launch vehicle to enable movement from Earth to orbit and from Earth orbit to the Moon and beyond; cargo transportation systems for fuel, supplies, and infrastructure; surface systems for transportation, power, and habitation; in-space systems for communications, maintenance, and supply; ground systems to support mission simulation, preflight integration, flight operations, and testing; and scientific and maintenance instrumentation. In most of these areas, Project Constellation will be responsible for developing new systems to provide the capabilities needed. In other areas, such as in-space systems, Project Constellation will work with other NASA offices and programs to obtain the necessary capabilities by enhancing existing systems.

The capabilities of Project Constellation systems are expected to evolve over time, based on exploration goals, budgetary priorities, and analyses of costs, benefits, and risks. NASA's current plans anticipate that first flight of the CEV will occur in 2011, and that astronauts will return to the Moon no later than 2020.[3,4]

The Development Programs Division of the Office of Exploration Systems is organized as follows:

A. Constellation Systems
   - Crew vehicle
   - Transportation systems
   - Supporting surface systems

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[1] See, for example, National Aeronautics and Space Administration, *Explorations Systems Interim Strategy*, NP-2004-07-362-HQ, Washington, D.C.: NASA Headquarters. August 2004. Available online at <www.exploration.nasa.gov/index.html>.

[2] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on the Implementation of United States Space Exploration Policy*, June 2004. Available online at <http://govinfo.library.unt.edu/moontomars/notices/contact.asp>.

[3] National Aeronautics and Space Administration. 2004. *Constellation Systems: Capabilities to Enhance Space Exploration*. Available online at <www.exploration.nasa.gov/constellation.html>.

[4] *Explorations Systems Interim Strategy*, NP-2004-07-362-HQ, Washington, D.C.: NASA Headquarters. August 2004. Available online at <www.exploration.nasa.gov/index.html>.

- Supporting in-space systems
- Transition programs
- Mission operations
- Robotic lunar orbiters and landers
- Launch vehicles

B. Prometheus Nuclear Technology
- Jupiter Icy Moons Orbiter (which is expected to demonstrate technology that will be of value for the exploration of the Moon and Mars)
- Radioisotope power systems
- Advanced systems development (which includes consideration of space nuclear reactor power and propulsion systems)

C. Research and Technology Development
- Exploration systems research and technology
- Human system research and technology

For the purposes of assessing systems integration approaches, the committee took a broad view of Project Constellation. In particular, the committee believes that the Project Constellation systems integrator should have the domain knowledge and expertise to integrate all of the work being executed by the Development Programs Division, with the exception of the Hubble Space Telescope Rescue Service Mission. This scope would include the basic Project Constellation systems (Group A, above), as well as elements of the nuclear technology being developed for Project Constellation by the Prometheus Project (Group B) and supporting research and technology efforts (Group C). (The committee did not attempt to determine if there are other projects within NASA that might benefit from being included in Project Constellation.)

The U.S. vision for space exploration could be pursued with a number of alternative systems and system architectures, some with widely differing capabilities, costs, and schedules. The services of a highly capable systems integrator will be an important asset in determining the way forward. Based on the Project Constellation schedule, it is urgent to rapidly establish and implement a systems integration capability. Thus, timeliness is an important factor affecting the assessment of alternate systems integration approaches, especially for the option of creating a new company to be the systems integrator.

SYSTEMS INTEGRATION SCOPE

The Office of Exploration Systems has defined Project Constellation in terms of six tiers:

- Tier 1. Enterprise Elements: Project Constellation (a system of systems)
- Tier 2. System (e.g., crew transport system, surface systems)
- Tier 3. Segment (e.g., CEV, launch vehicle, ground segment)
- Tier 4. Element (e.g., booster element)
- Tier 5. Subsystem (e.g., booster main engine)
- Tier 6. Assembly (e.g., thrust chamber assembly)

Standing above all of these are the Level 0 vision and requirements. This report assesses potential approaches for systems integration at Tiers 1 and 2 by considering the likelihood that each surrogate organization would be able to meet cost and schedule requirements in the completion of relevant tasks, such as those listed in Attachment D. The assessments that follow do not necessarily apply to systems integration at other tiers, although, at Tiers 1 and 2, the systems integrator will have knowledge of, cognizance of, and influence on what is happening at Tier 3.

CRITERIA

The committee generated a list of 21 criteria that relate to the ability of a systems integrator to foster success with a complex space exploration project such as Project Constellation. The criteria fall into the five categories listed below. The categories—and the criteria within each category—are listed in priority order.

A. Systems Integration Essentials
   1. Domain knowledge and experience encompassing the full breadth of Project Constellation.
   2. Systems engineering talent, experience, tools, processes, and facilities, including simulation and test capabilities.
   3. Demonstrated understanding of requirements and their interrelationships.
   4. Cost and schedule controls.
   5. Ability to manage complex interfaces between scientific and engineering organizations, including international partners.
   6. Ability to facilitate infusion of advanced technology from many sources.
   7. Independent assessment of technical performance, such as power and weight.

B. General Program Management Effectiveness
   1. Project management experience and discipline.
   2. Ability to accurately predict costs and required reserves.
   3. Effective technology management and transition process for risk reduction.
   4. Incorporating cost and schedule management into the systems integration function.

C. Cost and Economic Leverage
   1. Ability to achieve best value for total program.
   2. Ability to conduct timely trade studies to define system architectures that minimize cost and risk.
   3. Ability to effectively and constructively assist NASA with deliberations with the Office of Management and Budget (OMB) and Congress.
   4. Ability to leverage resources from the U.S. Department of Defense and other U.S. and international government organizations.

D. Stability
   1. Agility and flexibility to accommodate changing national priorities over unprecedentedly long periods.
   2. Ability to motivate, educate, recruit, and retain required talents (in government, industry, and academia).
   3. Ability to articulate mission goals internally and externally.

E. Public and Political Credibility
   1. Knowledge of political processes.
   2. Credible and recognized nonpartisan authority.
   3. Knowledgeable and objective resource to the federal government.

SURROGATE ORGANIZATION DEFINITIONS

To facilitate the process of evaluating the four approaches listed in its statement of task, the committee characterized seven generic organizations to use as surrogates, as follows:

1. NASA as systems integrator
   a. Center-centric systems integration
   b. Headquarters-centric systems integration
2. Large aerospace company as systems integrator
   a. Company with no hardware exclusion
   b. Company with a partial hardware exclusion
   c. Company with a complete hardware exclusion
3. Nonaerospace company as systems integrator
4. New organization as systems integrator

Each of these surrogate organizations is defined below.

Approach 1 Defined: NASA as Systems Integrator

NASA would be the systems integrator. The technical expertise of NASA's civil service workforce would be supported by an on-site support contractor experienced in system engineering and integration. The support contractor would have a complete hardware exclusion.

Systems integration, particularly at the Tier 1 level, will require a strong capability in both robotic and human spaceflight as well as the interaction of the two. As a result, the strength of the systems integration team can only be as strong as its weakest link. As illustrated in the section below entitled "Additional Systems Integration Considerations," it is the consensus of the committee that NASA's capabilities in human spaceflight systems engineering and integration have eroded over the years, but its capabilities in robotic spaceflight are now very strong. This makes NASA's current internal expertise in human spaceflight systems integration the factor upon which this option must be judged. The committee's assessment of this option reflects this conclusion.

Approach 1a. Center-centric Systems Integration

A single office located at one of the NASA Centers would have primary responsibility for systems integration, program execution, and contract authority at Tier 1. At lower tiers, responsibility for these areas would, in some cases, be located at geographically distant subordinate offices. NASA Headquarters would have overall program responsibility, allocating work and budget to the Centers. Headquarters would have a spartan technical staff responsible for overall system architecture, monitoring the systems integration and implementation effort, and it would provide leadership for important program-level decisions.

Approach 1b. Headquarters-centric Systems Integration

NASA Headquarters would have responsibility for program leadership, decision authority, systems integration, and contract authority. Centers would provide technical expertise and execute major program elements as directed by NASA Headquarters. Some Center personnel would be relocated to NASA Headquarters to augment existing staff.

Approach 2 Defined: Large Aerospace Company as Systems Integrator

The committee examined three variations on this approach.

Approach 2a. Company with No Hardware Exclusion

The systems integrator would have no hardware exclusion in providing Project Constellation hardware. Systems integrators normally require access to some proprietary data from key hardware vendors. Thus, for this approach, the systems integrator could have access to proprietary data from companies that it is competing against in hardware procurements. Firewalls between separate parts of the organization would be established to avoid conflicts of interest, but that might not satisfy some other hardware vendors or avoid the appearance of perceived conflicts of interest.

Approach 2b. Company with a Partial Hardware Exclusion

The systems integrator would be limited to a minor role in providing Project Constellation hardware. Any hardware provided by the systems integrator would be through subcontracts with Project Constellation prime hardware contractors. Firewalls would separate parts of the organization to avoid conflicts of interest.

Approach 2c. Company with a Complete Hardware Exclusion

The systems integrator would not be allowed to provide any Project Constellation hardware. This could be an organization with few or no manufacturing capabilities, or a hardware vendor that agrees to forego the opportunity to bid on Project Constellation hardware procurements.

Approach 3 Defined: Nonaerospace Company as Systems Integrator

The systems integrator would be a large nonaerospace company with a complete hardware exclusion. It would be experienced in systems integration on large, complex projects, nationally and internationally.

Approach 4 Defined: New Organization as Systems Integrator

The systems integrator would be a for-profit or nonprofit organization with a complete hardware exclusion. The organization would be formed with the active participation of existing organization(s) with space experience. It would not be subject to civil service regulations. The talent assembled to create this organization would include a significant number of people from the space community in government and industry, so it would have the proper experience base. It could take considerable time to assemble the talent and bring this organization to full operational capacity.

The committee recognizes that for each type of organization, there are additional variations beyond those defined above. The performance of any organization that varies from these definitions would differ from the performance defined by the committee in the following section. For example, the performance of a given organization will vary depending upon how the surrogate is organized to balance the needs for (1) centralized management, information, and control at Tier 1 and (2) distributed authority and responsibility at lower tiers.

The criteria defined above and the considerations that the committee used in assessing the seven surrogate organizations should assist NASA in making an accurate assessment of whatever specific approaches and organizations it must ultimately evaluate in selecting the Project Constellation systems integrator. In particular, Table 1 (below) was prepared in a way that should help NASA management assess hybrid approaches based on the attributes of individual surrogate organizations. For, example, the idea of forming a federally funded research and development center (FFRDC) from one or more NASA Centers could be evaluated using the committee's assessments of options 1a and 4.

SURROGATE ORGANIZATION ASSESSMENT

Table 1 provides the committee's comparative assessment of how each of the seven surrogate organizations would perform as measured by each criterion. The strengths and weaknesses noted for each approach apply to the ability of the surrogate organizations to fulfill the role of prime systems integrator and should not be used to characterize the ability of the surrogate organizations to contribute their expertise to Project Constellation in other ways. For example, some nonaerospace companies have a great deal of expertise in areas relevant to Project Constellation, but as noted in Table 1, selecting them to serve as the prime systems integrator may not be the best way to incorporate this expertise into Project Constellation. Also, regardless of which approach is chosen, additional factors beyond the criteria that appear in Table 1 are essential to the successful performance of the systems integrator and Project Constellation as a whole. Many of these factors are addressed in the final section of this report, "Additional Systems Integration Considerations."

The arrows in Table 1 signify the committee's judgment of the relative strength of each approach as it relates to each criterion, as follows:

 Can do exceptionally well

 Can do with improvements

 Can do

 Major deficiencies

The committee's assessment of each surrogate organization is summarized following Table 1. In accordance with the statement of task, the committee makes no recommendation regarding which systems integration approach NASA should use. In particular, no conclusions should be drawn based on the number of strengths and weaknesses listed for each surrogate organization, because individual strengths and weaknesses are not of equal significance.

Table 1 Comparative Assessment of Systems Integration Approaches for Project Constellation

Criteria (by Category)	Approach / Systems Integration Organization						
	1. NASA		2. Aerospace Company			3. Nonaerospace Company	4. New Organization
	a. Center-Centric	b. HQ-Centric	a. No Hardware Exclusion	b. Partial Hardware Exclusion	c. Complete Hardware Exclusion		
A. SYSTEMS INTEGRATION ESSENTIALS							
1. Domain knowledge and experience encompassing the full breadth of Project Constellation.	[Can do] Has clear understanding of scope. Center personnel have done it before. In human spaceflight, there has been an erosion of talent, but skills could be augmented with internal transfers and/or support contractors.	[Can do with improvements] Has clear understanding of scope. Requires formation of new teams. Less depth of talent. In human spaceflight, there has been an erosion of talent. Skills could be augmented with support contractors, but it would be difficult to augment skills with internal transfers.	[Can do] Clearly possesses the skills and knows what is required. Able to attract the best companies and people.	[Can do with improvements] Clearly possesses the skills and knows what is required. May not attract some qualified companies or people because of the partial hardware exclusion.	[Can do with improvements] Clearly possesses the skills and knows what is required. Unlikely to attract some qualified companies or people.	[Major deficiencies] Lacks indigenous space experience; teaming would be necessary.	[Can do with improvements] Able to attract the best people, but creating an experienced organization would take time.
2. Systems engineering talent, experience, tools, processes, and facilities, including simulation and test capabilities.	[Can do with improvements] Talent exists. System development talent has eroded in human spaceflight, but could be augmented from within NASA and/or through support contractors. Would be the highest-priority program in the organization. Tools and processes exist, but need to be adapted. Excellent facilities and test capabilities.	[Major deficiencies] Talent may exist, but must be relocated. Skills could be augmented with support contractors, but it would be difficult to augment skills with internal transfers. Would be the highest-priority program in the organization. Tools and processes must be acquired. No local facilities or test capabilities.	[Can do] Capability exists.	[Can do] Capability exists if best people and tools are applied. May not be the highest-priority program in the organization. Facilities and test capabilities could be augmented.	[Can do with improvements] Capability exists if best people and tools are applied. May be a low-priority program within the organization. Facilities and test capabilities could be augmented. May not attract some qualified companies.	[Major deficiencies] Could have good systems engineering skills, especially with regard to ground systems, but tools, processes, facilities, and overall capabilities would have to be augmented by teaming for space systems.	[Can do with improvements] Capability could be built in or incorporated from chartering organization(s), but start-up time would be required.

(continued)

[Can do exceptionally well] = Can do exceptionally well, [Can do] = Can do, [Can do with improvements] = Can do with improvements, [Major deficiencies] = Major deficiencies.

Table 1 Comparative Assessment of Systems integration Approaches for Project Constellation (continued)

Criteria (by Category)	Approach / Systems Integration Organization						
	1. NASA		2. Aerospace Company			3. Nonaerospace Company	4. New Organization
	a. Center-Centric	b. HQ-Centric	a. No Hardware Exclusion	b. Partial Hardware Exclusion	c. Complete Hardware Exclusion		
3. Demonstrated understanding of requirements and their interrelationships.	↑ Excellent insight.	↑ Excellent insight.	↗ Good insight.	↗ Good insight.	↗ Good insight.	↓ Understands the mechanics but not the space context.	↓ Capability could be built in or incorporated from chartering organization(s), but start-up delay would be critical.
4. Cost and schedule controls.	↓ Basic project management discipline requires significant improvement. Poor recent track record in human spaceflight. Amorphous program definition aggravates this problem.	↓ Basic project management discipline requires significant improvement. Poor recent track record in human spaceflight. Amorphous program definition aggravates this problem.	↘ Effective control processes exist. Poor recent track record. Contracting incentives will help ensure application of best processes.	↘ Effective control processes exist. Poor recent track record. Contracting incentives will help ensure application of best processes.	↘ Effective control processes exist. Poor recent track record. Contracting incentives will help ensure application of best processes.	↗ Effective processes and good track record. Contracting incentives highly effective.	↘ Effectiveness depends on processes derived from chartering organization(s).
5. Ability to manage complex interfaces between scientific and engineering organizations, including international partners.	↑ Good demonstrated capability.	↘ Lacks demonstrated capability. Similar systems integration efforts by NASA in the past have failed.	↑ Good demonstrated capability.	↑ Good demonstrated capability.	↑ Good demonstrated capability.	↑ Good demonstrated capability.	↘ Could be built in or incorporated from chartering organization(s).
6. Ability to facilitate infusion of advanced technology from many sources.	↘ Demonstrated flexibility in adopting flow of new technologies. Better insight and partnering needed with industry and universities.	↘ Demonstrated flexibility in adopting flow of new technologies. Better insight and partnering needed with industry and universities.	↗ Demonstrated flexibility in adopting flow of new technologies.	↗ Demonstrated flexibility in adopting flow of new technologies.	↗ Demonstrated flexibility in adopting flow of new technologies.	↘ Would be objective but would require NASA input in many cases. Technology recognition and technology pull likely to be weak.	↘ Potential for technology adoption. Would be low-priority task in the organization.
7. Independent assessment of technical performance, such as power and weight.	↑ Good demonstrated capability.	↗ Lacks demonstrated capability, but capability could be acquired with a relatively small number of personnel transfers.	↓ Good demonstrated capability, but potentially irresolvable problems accessing information from competitors.	↗ Good demonstrated capability, but potential problems accessing information from competitors.	↑ Good demonstrated capability.	↗ Capable, but subject matter experts would be necessary.	↗ Could be hired or incorporated from chartering organization(s).

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Table 1 Comparative Assessment of Systems Integration Approaches for Project Constellation (continued)

Criteria (by Category)	Approach / Systems Integration Organization: 1. NASA: a. Center-Centric	1. NASA: b. HQ-Centric	2. Aerospace Company: a. No Hardware Exclusion	2. Aerospace Company: b. Partial Hardware Exclusion	2. Aerospace Company: c. Complete Hardware Exclusion	3. Nonaerospace Company	4. New Organization
B. GENERAL PROGRAM MANAGEMENT EFFECTIVENESS							
1. Project management experience and discipline.	↗ Extensive and continuous experience in managing space exploration projects. Discipline in human spaceflight needs improvement.	↓ Little experience in managing space exploration projects. Discipline in human spaceflight needs improvement.	↗ Extensive experience in managing space exploration projects.	↗ Extensive experience in managing space exploration projects, but may not attract some qualified companies.	↘ Unlikely to attract some qualified companies.	↓ Has ground systems experience, but unlikely to have space experience or acquire it in a timely manner.	↓ Unlikely to acquire experience in a timely manner.
2. Ability to accurately predict costs and required reserves.	↓ Ability not demonstrated. Capability exists in robotics programs.	↓ Ability not demonstrated. Capability exists in robotics programs.	↗ Has the ability; also has potential conflicts within own company and with competitors.	↗ Has the ability; also has potential conflicts within own company and with competitors.	↘ Unlikely to attract some qualified companies.	↘ Has capability with regard to ground systems, but lacks space experience.	↓ Unlikely to obtain necessary capability in a timely manner.
3. Effective technology management and transition process for risk reduction.	↘ Has not been effective in this function in past programs; should be able to improve.	↘ Has not been effective in this function in past programs; should be able to improve.	↗ Most large aerospace companies have proven processes.	↗ Most large aerospace companies have proven processes.	↘ Unlikely to attract some qualified companies.	↘ Has capability with regard to ground systems, but lacks space experience.	↘ Could develop the capability; timing not critical.
4. Incorporating cost and schedule management into the systems integration function.	↘ Has not been effective in this function in past programs; should be able to improve.	↘ Has not been effective in this function in past programs; should be able to improve.	↗ Most large aerospace companies have proven processes.	↗ Most large aerospace companies have proven processes.	↘ Unlikely to attract some qualified companies.	↘ Has capability with regard to ground systems, but lacks space experience.	↓ Unlikely to obtain necessary capability in a timely manner.
C. COST AND ECONOMIC LEVERAGE							
1. Ability to achieve best value for total program.	↘ Performed well in robotic and earlier spaceflight programs, but needs to improve performance in human spaceflight programs.	↓ Lacks demonstrated capability. Similar systems integration efforts by NASA in the past have failed.	↓ Good demonstrated capability, but potentially irresolvable problems in accessing information from competitors.	↘ Able to deliver good value given the proper environment, but has potential problems in accessing information from competitors.	↘ Unlikely to attract some qualified companies.	↓ Has capability with regard to ground systems, but unlikely to have required space experience.	↓ Potential to obtain experience; timeliness an issue.

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Table 1 Comparative Assessment of Systems integration Approaches for Project Constellation (continued)

Criteria (by Category)	Approach / Systems Integration Organization						
	1. NASA		2. Aerospace Company			3. Nonaerospace Company	4. New Organization
	a. Center-Centric	b. HQ-Centric	a. No Hardware Exclusion	b. Partial Hardware Exclusion	c. Complete Hardware Exclusion		
2. Ability to conduct timely trade studies to define system architectures that minimize cost and risk.	↗ Good capability.	↗ Good capability.	↓ Problems in accessing information from competitors for trade studies.	↗ Good capability, but may have some problems in accessing information from competitors for trade studies.	↗ Good capability.	↘ Has capability with regard to ground systems, but lacks space expertise.	↘ Capability could be developed.
3. Ability to effectively and constructively assist NASA with OMB and congressional deliberations.	Not applicable.	Not applicable.	↘ Limited credibility because of competitive environment.	↑ Full capability to assist.	↑ Full capability to assist.	↗ Full capability to support, but requires new government relationships.	↘ Lacks leverage because of limited size and scope of organization.
4. Ability to leverage resources from the U.S. Department of Defense and other U.S. and international government organizations.	↗ Excellent potential, but past performance is mixed.	↗ Excellent potential, but past performance is mixed.	↗ Broad customer base enhances ability to leverage other investments.	↗ Broad customer base enhances ability to leverage other investments.	↘ Unlikely to attract some qualified companies, which could limit exposure to other government entities.	↓ Unlikely to have access to relevant space technologies.	↓ Narrow base: focused on space exploration.
D. STABILITY							
1. Agility and flexibility to accommodate changing national priorities over unprecedentedly long periods.	↗ Provides understanding and continuity; support contractors provide flexibility.	↑ Provides understanding and continuity; support contractors provide flexibility. Closer to decision makers than the Centers.	↘ Can maintain the appropriate talent, but requires reasonably stable funding.	↘ Can maintain the appropriate talent, but requires reasonably stable funding.	↘ Can maintain the appropriate talent, but requires reasonably stable funding.	↘ Can maintain the appropriate talent, but requires reasonably stable funding.	↓ Has less flexibility under funding fluctuations, plus potential start-up problems.

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Table 1 Comparative Assessment of Systems Integration Approaches for Project Constellation (continued)

Criteria (by Category)	Approach / Systems Integration Organization						
	1. NASA		2. Aerospace Company			3. Nonaerospace Company	4. New Organization
	a. Center-Centric	b. HQ-Centric	a. No Hardware Exclusion	b. Partial Hardware Exclusion	c. Complete Hardware Exclusion		
2. Ability to motivate, educate, recruit, and retain required talents (in government, industry, and academia).	↘ Reputation facilitates recruitment, but difficult to compete financially with industry in (1) hiring experienced staff and (2) retaining all required talents, even with new personnel legislation.	↓ Reputation facilitates recruitment, but difficult to compete financially with industry in (1) hiring experienced staff and (2) retaining all required talents, even with new personnel legislation. Washington, D.C., location makes recruitment and relocation especially difficult.	↗ Competitive hiring practices.	↗ Competitive hiring practices.	↗ Competitive hiring practices.	↘ Competitive hiring practices, but may have problems attracting space professionals.	↓ Unsure career path may make it difficult to hire staff. Timeliness is also an issue.
3. Ability to articulate mission goals internally and externally.	↑ Owns the mission	↑ Owns the mission.	↗ Long history of success.	↗ Long history of success.	↗ Long history of success.	↘ Long history of success with ground systems, but lacks corporate credibility in space.	↗ Could be appropriately designed to deal with this issue, but start-up issues possible.
E. PUBLIC AND POLITICAL CREDIBILITY							
1. Knowledge of political processes.	↑ Excellent understanding of political processes. Ability to work within the system.	↑ Excellent understanding of political processes. Ability to work within the system.	↑ Vast experience, knowledge, and understanding of political processes.	↑ Vast experience, knowledge, and understanding of political processes.	↑ Vast experience, knowledge, and understanding of political processes.	↗ Excellent understanding of political processes; lacks relationships with congressional committees related to space.	↘ Needs to develop credibility.
2. Credible and recognized nonpartisan authority.	↗ Credible, but potentially perceived as biased.	↗ Credible, but potentially perceived as biased.	↓ Perceived conflict of interest.	↗ Credible, but potentially perceived as biased.	↗ Fewer perceived biases than other industry options.	↘ Has capability with ground systems, but lacks space experience.	↘ Start-up problems.
3. Knowledgeable and objective resource to federal government.	↑ Very knowledgeable.	↑ Very knowledgeable.	↘ Perceived conflict of interest.	↗ Knowledgeable.	↗ Knowledgeable.	↘ Has capability with ground systems, but lacks space expertise.	↘ Start-up problems.

Approach 1 Assessed: NASA as Systems Integrator

NASA has a strong history and continuity of experience in human and robotic space missions. This background results in excellent understanding of the requirements for success in the space environment, demonstrated skills in management of systems interfaces, and the ability to interact successfully with various government entities involved in the approval, funding, and support of space activities. NASA has outstanding facilities and is likely to be able to sustain a long-term program such as Project Constellation through many years of changing conditions and priorities. In addition, regardless of the approach selected, Project Constellation creates an opportunity for NASA to develop the next generation of NASA space exploration scientists, engineers, and program managers to lead the agency into the future.

For Approaches 1a (Center-centric) or 1b (Headquarters-centric), there is a major risk to the success of Project Constellation in that the human spaceflight organization has suffered in recent years from an erosion of knowledge, experience, and skills as the program focus has shifted from engineering and development to operations. This change has resulted in the degradation of its capabilities in systems engineering, program management discipline, cost and schedule management, and technology management for risk reduction. Although NASA's position and reputation are attractive to potential recruits, it has difficulty competing financially with commercial firms and thus is at a disadvantage in retaining the most talented personnel.

The situation described above can be improved by transferring into the human spaceflight systems integration organization personnel, methods, and expertise from other NASA organizations, as well as through further partnering with industry and universities, although relocating personnel from the Centers to NASA Headquarters (for Approach 1b) would be difficult.

Approach 1a. Center-centric Systems Integration

The strengths and weaknesses of Approach 1a are summarized as follows:

- Strengths:
  - ability to maintain a strong commitment over decades
  - broad technical expertise in robotic spacecraft
  - continuity of expertise
  - experience with managing industrial teams
  - in-depth space experience
  - international experience with companies and governments
  - likely access to senior government officials
  - no financial conflicts of interests
  - not conflicted in management of requirements process

- Weaknesses:
  - erosion of human spaceflight development capability
  - inability to compete well for talent on a salary basis
  - leadership changes due to administration changes
  - limited geographic political base
  - little or no hardware manufacturing experience
  - poor cost and schedule controls in human spaceflight

Approach 1b. Headquarters-centric Systems Integration

The strengths and weaknesses of Approach 1b are summarized as follows:

- Strengths:
  - ability to maintain a strong commitment over decades
  - international experience with companies and governments
  - no financial conflicts of interests
  - not conflicted in management of requirements process
  - ready access to senior government officials

- Weaknesses:
  - difficult to relocate staff to Washington, D.C.
  - erosion of human spaceflight development capability
  - inability to compete well for talent on a salary basis
  - leadership changes due to administration changes
  - limited experience with managing industrial teams
  - limited geographic political base
  - limited space experience
  - little or no hardware manufacturing experience
  - need to create new teams
  - poor cost and schedule controls in human spaceflight

Approach 2 Assessed: Large Aerospace Company as Systems Integrator

Approach 2a. Large Aerospace Company with no Hardware Exclusion

Approach 2a has a strong skill base from which to draw. Several large aerospace companies have a great deal of experience, effective management methods, and successful records of managing complex space programs. They are experienced and skilled at political interactions and have a successful record of adopting external new technologies. They have an advantage in attracting and retaining personnel because of salary flexibility, provided they can achieve continuity of program funding.

It will be difficult for a company acting as both the systems integrator and a major hardware contractor to avoid real or perceived conflicts of interest, which will reduce its credibility in representing the program to the government and the public. It will also have a great deal of difficulty in accessing information from competitive prime contractors, and other hardware vendors could be expected to strongly resist being managed by this kind of systems integrator in situations that would require the sharing of proprietary data. This is a potentially unsolvable problem that could preclude this alternative. In any case, this approach would likely reduce the incentive for contractors other than the systems integrator to bid on some Project Constellation hardware procurements. A commercial firm is also more vulnerable to budget and schedule changes over the long life of this program. Commercial firms have concerns similar to those of NASA in terms of program cost and schedule delivery. The strengths and weaknesses of Approach 2a are summarized as follows:

- Strengths:
    - ability to establish attractive employee compensation packages
    - access to senior administration officials
    - aerospace design and management tools
    - in-depth space experience, including space hardware manufacturing experience
    - international experience with companies and governments
    - potentially large geographic political base
    - relatively stable leadership
    - systems integration management experience

- Weaknesses:
    - possibility that hardware procurements will have higher corporate priority than systems integration
    - possibility that teammates will resist being managed
    - potentially irresolvable conflicts of interest
    - substantial difficulty in accessing information from some other contractors

Approach 2b. Large Aerospace Company with a Partial Hardware Exclusion

Approach 2b shares the advantages of Approach 2a in skill base, salary structure, and political interactions. It also shares the vulnerability to budget and schedule changes. The limited hardware role, however, may not be attractive to some qualified companies, or to the best people from the companies that do bid. Also, because of the hardware exclusion, the program may not be of the highest priority to the company. There are still potential problems in accessing information from competitive prime contractors, but they are reduced in severity compared to Approach 2a, and there is less concern with potential conflicts of interest. The strengths and weaknesses of Approach 2b are summarized as follows:

- Strengths:
    - ability to establish attractive employee compensation packages
    - access to senior administration officials
    - aerospace design and management tools
    - in-depth space experience, including space hardware manufacturing experience
    - international experience with companies and governments
    - potentially large geographic political base
    - relatively stable leadership
    - systems integration management experience

- Weaknesses:
    - possibility that some prime contractors will elect not to assume this role because it would limit their ability to provide Project Constellation hardware
    - possibility that teammates will resist being managed
    - some difficulty in accessing information from some other contractors
    - some possible conflicts of interest

Approach 2c. Large Aerospace Company with a Complete Hardware Exclusion

Approach 2c shares most of the strengths and weaknesses of Approach 2b. The lack of hardware content mitigates the problem of access to competitors' information. However, it also means that at least some qualified companies and personnel will not find the opportunity attractive, and companies that have already committed themselves to provide hardware will not be able to submit a bid to be the systems integrator. Also, because of the hardware exclusion, the program may not be of the highest priority within the company. The strengths and weaknesses of Approach 2c are summarized as follows:

- Strengths:
  - ability to establish attractive employee compensation packages
  - access to senior administration officials
  - aerospace design and management tools
  - in-depth space experience, possibly including space hardware manufacturing experience
  - international experience with companies and governments
  - potentially large geographic political base
  - relatively stable leadership
  - systems integration management experience

- Weaknesses:
  - possibility that some prime contractors will be unable to assume this role because of ongoing contracts to provide Project Constellation hardware
  - possibility that some prime contractors will elect not to assume this role because it would limit their ability to provide Project Constellation hardware

Approach 3 Assessed: Nonaerospace Company as Systems Integrator

Some nonaerospace companies have excellent tools, skills, and track records in the mechanics of systems integration, cost and schedule prediction and control, adoption and infusion of new external technologies, government relations, and salary flexibility. The expertise of some large nonaerospace companies could also directly contribute to the development and integration of large, complex surface systems and infrastructure, which will ultimately represent a large portion of the overall cost of Project Constellation. Even so, significant weaknesses arise from the lack of space experience of these companies. Teaming with space-experienced contractors could mitigate problems in areas such as the adoption of methods, processes, and facilities; recognition and pull of certain new technologies; and prediction of cost and schedule drivers that are unique to space. However, teaming is unlikely to resolve problems with attracting space professionals, credibility with the space industry and congressional committees, access to the U.S. Department of Defense and other government technology sources, and overall value. Of particular concern is the time that would be required to develop the necessary capabilities in areas such as project management and discipline, systems engineering, and requirements definition. The strengths and weaknesses of Approach 3 are summarized as follows:

- Strengths:
  - ability to establish attractive employee compensation packages
  - access to senior administration officials
  - experience in the development of large, complex grounds systems and infrastructure
  - international experience
  - management tools

  - minimal public perception of conflicts
  - potentially large geographic political base
  - relatively stable leadership

- Weaknesses:
  - little or no organic space knowledge
  - little or no space hardware manufacturing experience
  - little understanding of space technology and requirements
  - possible negative public perception from limited space experience

Approach 4 Assessed: New Organization as Systems Integrator

Establishing a new organization carries significant risk from start-up delays, particularly in attracting qualified personnel, consolidating domain knowledge, understanding requirements, building relationships, establishing cost control and program management disciplines, institutionalizing methods and processes, and bringing up facilities. Approach 4 is also highly dependent on the processes, methods, and personnel received from the chartering organization(s).

A new organization, once established, would be more focused than the other surrogate organizations because it would be constructed to serve a specific mission, and it would not have to deal with the institutional inertia of an existing organization implementing a new mission. A new organization, however, would also be highly vulnerable to budget fluctuations since it would not have other activities for personnel to move to, and an uncertain career path could make recruiting and retention difficult. The strengths and weaknesses of Approach 4 are summarized as follows:

- Strengths:
  - ability to establish attractive employee compensation packages
  - ability to recruit and keep dedicated technical and management talent
  - absence of any conflicts of interest
  - strong access to U.S. political leadership (with the right leadership)
  - total dedication

- Weaknesses:
  - difficulty of establishing and maintaining sufficient authority to control prime contractors
  - need to establish a new organization and get up to speed quickly
  - difficulty of developing a strong geographic spread
  - lack of hardware manufacturing experience
  - organizational inflexibility, since the company would have no other projects
  - need to set up requisite analysis, simulation, and management tools

ADDITIONAL SYSTEMS INTEGRATION CONSIDERATIONS

The committee believes that certain basic factors are critical to the success of the systems integration function for Project Constellation, regardless of which approach is chosen. These factors are described briefly below.

Functional Alignment

It is imperative that systems integration for Project Constellation be closely aligned with the technical capability and the appropriate contracting and budgetary control authority. This should be done at a facility and in an organization that has a strong, indigenous management systems capability, with clear lines of authority and responsibility.

Time Phasing

Project Constellation requires a strong systems integration capability at the earliest possible date to ensure that all systems integration elements are properly established. Otherwise, elements of the program may not be appropriately sequenced and effectively integrated, which could result in major cost and schedule consequences. Moreover, if hardware contracts are awarded before the systems integration function is established, the list of potential systems integration contractors could be significantly depleted by virtue of hardware exclusion provisions. The committee is concerned that the Project Constellation plan presented to the committee may not put in place adequate systems integration capabilities before hardware development begins.

Staffing

A space systems experience base is necessary for the success of any systems integration approach for Project Constellation. Space is different from other high-technology endeavors. User requirements typically push space programs to the cutting edge of technology with virtually no tolerance for subsystem failures. The total program consists of a small number of systems, and the first one launched is almost always fully operational.

Space systems operate in a hostile environment with remote operations. Success depends upon minimizing human errors and design flaws using testing, independent review, and oversight. One undetected mistake or error can be catastrophic. A single mission failure can have enormous national implications, especially for human spaceflight. For these reasons, space experience is required for the successful implementation of space projects, and the potential effects of using unproven methods and technologies must be carefully considered before they are adopted. For example, several ongoing acquisition programs, such as the Joint Strike Fighter, are using the lead systems integrator model, but none of these programs has yet reached the stage of delivering operational hardware, so it is too soon to make a final assessment of this model.

Strengthening the state of systems engineering is also critical to the long-term success of Project Constellation. A competent systems engineering capability must be resident within the government and industry. The U.S. Department of Defense essentially eliminated its systems engineering capability as a result of acquisition reforms implemented in the 1990s. NASA's human spaceflight systems engineering capability has eroded significantly as a result of declining engineering and development work, which has been replaced by operational responsibilities. Industry has a credible systems engineering capability, but it is being stressed by the need to modernize almost all national security space programs. The demand for experienced systems engineers, who can function credibly in a system-of-systems environment, is particularly acute.

Understanding the state of systems engineering is of the utmost importance in selecting management concepts for implementing Project Constellation. Plans should be developed for maintaining a satisfactory base of systems engineering throughout the duration of this program.

Structure for Mission Success

The probability of mission success is enhanced by establishing clear goals and schedule objectives. The Apollo Program had the advantage of a clear schedule imperative, a singular goal, and a sense of national purpose that enabled NASA to recruit the best and brightest from government, industry, and academia; preserved the budget; and drove execution on a daily basis. Project Constellation, on the other hand, is more of a "journey" with evolving and diverse goals, an elastic schedule with disparate programs that extend over multiple decades, and an uncertain budget. Project Constellation is also likely to include international partners, which would further complicate the systems integration challenge.

A program of the scope and duration of Project Constellation will encounter programmatic and budgetary turbulence and instability. It is very likely that changing priorities and annual budget pressures—within the U.S. government and the governments of international partners—will necessitate numerous changes in the program plan and mission models. The capability to do ongoing "what-if" analyses that assess changes in cost, schedule, performance, and mission goals would keep Project Constellation in a proactive position and enable NASA to quickly respond to proposed changes while effectively communicating the full consequences of those changes to decision makers at NASA and OMB and in Congress.

The development of space systems is inherently risky. To achieve success, risk management must go far beyond corrective action prompted by incidents and accidents. All types of risk—including risk to human life—must be actively managed to achieve realistic and affordable goals. In addition, it should be noted that increasing schedule risk to compensate for funding shortfalls is not risk management; it is a form of risk capitulation.

In a program of this length, success will be measured and determined by the ability to recognize and promote developing technologies that can potentially play a significant role in mission achievement. Thus, the systems integrator should have an unusually strong ability to know, understand, and appreciate new and emerging technologies in a wide range of disciplines. This breadth of knowledge will require contacts with research activities in government, industry, and educational institutions and the encouragement and possible support of research that can play a significant role in optimizing mission effectiveness.

Lessons from the Past

The committee briefly reviewed how industry and government have conducted systems integration in large programs as far back as the Apollo Program and as recently as the Mars Exploration Program. Apollo, Skylab, and Apollo-Soyuz are examples of NASA human spaceflight programs that succeeded in terms of cost, schedule, and mission goals. This record of success has been tarnished by the increased cost, delayed schedule, and reduced technical capability of the International Space Station. Government and industry have experienced similar problems in the procurement of national security space programs.[5] Most recently there have been outstanding successes in robotic space exploration.

The Apollo Program demonstrated the importance of a balanced allocation of functions (including systems integration) between NASA Headquarters and Centers. The small staff at Head-

[5]Department of Defense. *Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs*. Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. May 2003. Available online at <www.fas.org/spp/military/dsb.pdf>.

quarters that was responsible for oversight of overall systems integration and architecture was supported by the extensive analytical and engineering resources of the Centers (especially Johnson Space Center, Marshall Space Flight Center, and Kennedy Space Center), where hardware contracts were issued and detailed systems integration was conducted. The analytical capability at NASA Headquarters was augmented by a support contract with Bellcom, which supported Headquarters and the Centers on Apollo systems issues. This allocation of functions is a potential model for the structure of Project Constellation, though some changes would be needed to account for important differences in NASA and industry capabilities that have developed since the Apollo Program.

NASA has initiated its own study of systems integration approaches that NASA and the Department of Defense have used in the past to develop advanced missiles, combat systems, aircraft, spacecraft, launch vehicles, and submarines.[6] NASA should reflect upon the results of that study both as it selects an approach to systems integration for Project Constellation and as it improves the systems integration capability of the human spaceflight program.

Project Constellation is an exciting concept and should serve to foster the continuation of the long tradition of NASA excellence. Good up-front systems design and integration in a program of this magnitude and complexity are of utmost importance. The committee urges NASA to select a systems integration approach quickly and to staff the selected approach adequately before making major commitments to hardware procurement. It is the hope of the committee that our evaluation of systems integration options will be of value to you in completing these difficult tasks. We offer our best wishes for your success.

Sincerely,

Donald C. Fraser, *Chair*
Committee on Systems Integration
for Project Constellation

Attachments
A Statement of Task
B Committee Membership—Roster and Biographies
C Program Briefings
D Systems Integration Tasks
E Optional Tasks
F Acknowledgment of Reviewers

[6] *Systems Engineering and Integration Organizational Considerations for Project Constellation (Draft).* National Aeronautics and Space Administration. Huntsville, Ala.: Marshall Space Flight Center. August 5, 2004.

Attachment A

Statement of Task

The Aeronautics and Space Engineering Board will assemble a study committee with approximately 12 members. The committee will hold one meeting lasting about four days and issue a letter report no later than September 15, 2004, that summarizes key aspects of its deliberations including findings and recommendations related to the following tasks:

1. Define criteria for assessing the relative merits of the four systems integration options detailed in Task 2. These criteria should identify those attributes required for the successful execution of Project Constellation. The committee may wish to consider such items as the characteristic features of successful systems integration organizations/cultures and whether all these features must be present in a single organization.

2. Evaluate the relative merits of the following options for performing the Project Constellation systems integration function:

   - government as prime integrator
   - one of the major hardware prime contractors is also integrator
   - an existing company (but not one of the Project Constellation prime contractors) is the integrator
   - government creates a new company to serve as integrator

3. If and only if time permits:

   - The committee should define metrics that could be used to measure progress of the systems integration activity.
   - In completing this task, the committee should evaluate the scope of the Project Constellation systems integration function, as defined by NASA. What part of the scope, such as approval of interface requirements, should remain a government function, regardless of which systems integration approach may be selected?
   - What specific skills, if any, should be subcontracted back to the government if the systems integrator is not a government organization?

The committee shall consider whether NASA has overlooked any applicable approaches or options for performing the Project Constellation systems integration function. The committee's deliberations will include the following factors/considerations:

- The scope and complexity of the Project Constellation requirements (as they are presented by NASA).
- The unique nature of the Project Constellation requirements.
- The ability of the existing "industrial base" associated with the above integration options.

- Legal constraints or regulations constraining any of the above options.
- Funding constraints/limitations associated with Project Constellation.
- Any other unique conditions identified by the committee.

To the extent that the study schedule permits, in performing this study the committee shall:

- Consider the systems integration approaches associated with selected previous and ongoing major aerospace initiatives (International Space Station, Hubble Space Telescope, Joint Strike Fighter, 777/7E7 Programs, etc.) and their relative strengths and weaknesses as they relate to Project Constellation.
- Consider the available capabilities that exist in government and industry to perform the Project Constellation systems integration function.

The scope of this project does not include the assessment of any particular technologies, system requirements, or system architectures; the capabilities of any specific organizations; the goals, feasibility, or budget of Project Constellation; or how NASA should be organized to carry out Project Constellation. Neither will the committee recommend which systems integration approach NASA should use.

Attachment B

Committee Membership—Roster and Biographies

COMMITTEE ON SYSTEMS INTEGRATION FOR PROJECT CONSTELLATION

DONALD C. FRASER, *Chair*, NAE, Former Principal Deputy Under Secretary of Defense for Acquisition; Former Executive Vice President, Draper Laboratory; Director, Boston University Photonics Center, Boston, Massachusetts

WILLIAM C. "BILL" BREEN, Vice President, Fluor Daniel (retired), Lake Forest, California

JOSEPH V. CHARYK, NAE, Former Under Secretary of the Air Force; Chairman and CEO, COMSAT Corporation (retired), Falmouth, Massachusetts

AARON COHEN, NAE, Former Acting Deputy Administrator of NASA; Former Director of NASA Johnson Space Center; Professor Emeritus of Engineering, Texas A&M University, College Station

RAYMOND S. COLLADAY, Former Associate Administrator of NASA; Former Director of the Defense Advanced Research Projects Agency; President, Lockheed Martin Astronautics (retired), Golden, Colorado

STEVEN D. DORFMAN, NAE, Vice Chairman, Hughes Electronics (retired), Los Angeles, California

ELVIN R. "VALD" HEIBERG III, NAE, Former Commander, U.S. Army Corps of Engineers; Lieutenant General, U.S. Army (retired); President, Heiberg Associates, Arlington, Virginia

KENT KRESA, NAE, Chairman Emeritus, Northrop Grumman Corporation, Beverly Hills, California

LESTER L. LYLES, Former Commander, U.S. Air Force Materiel Command; General, U.S. Air Force (retired), Vienna, Virginia

FRANK MARTIN, Former Director of Space Systems, Lockheed Martin; President, Martin Consulting, Inc., Morrisville, North Carolina

GEORGE A. PAULIKAS, Executive Vice President, The Aerospace Corporation (retired), El Segundo, California

JOHN B. PELLER, Vice President and Program Manager for Ground-based Midcourse Defense, The Boeing Company (retired), La Habra, California

HARRIS M. "BUD" SCHURMEIER, NAE, Associate Director, Jet Propulsion Laboratory (retired), Fallbrook, California

ROBERT C. SEAMANS, JR., NAE, Former Deputy Administrator of NASA; Former Secretary of the Air Force; Former Administrator, Energy Research and Development Administration; Professor Emeritus in Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge

JOHN K. WELCH, Executive Vice President, General Dynamics Corporation (retired), McLean, Virginia

F. GORDON WILLIS, Former Chief Engineer for Automatic Transmission Engineering, Ford Motor Company; Consultant, Gordon Willis Associates, Palm Beach, Florida

A. THOMAS YOUNG, NAE, Executive Vice President, Lockheed Martin (retired), Onancock, Virginia

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Note: NAE, National Academy of Engineering.

Aeronautics and Space Engineering Board Liaison to the Committee

WILLIAM W. HOOVER, Major General, U.S. Air Force (retired), Williamsburg, Virginia

Committee Staff

ALAN ANGLEMAN, Senior Program Officer
KARA BATH, Senior Project Assistant/Administrative Assistant
ANNA L. FARRAR, Financial Associate
NEERAJ GORKHALY, Administrative Assistant
GEORGE M. LEVIN, Director, Aeronautics and Space Engineering Board
CONNIE WOLDU, Administrative Assistant

BIOGRAPHIES OF COMMITTEE MEMBERS

DONALD C. FRASER, NAE, *Chair*, has broad research management experience and is the founder and director of the Boston University Photonics Center. Dr. Fraser received his B.S. and M.S. in aeronautics and astronautics and his Sc.D. in instrumentation from the Massachusetts Institute of Technology (MIT). He joined MIT's Instrumentation Laboratory (which became the Charles Stark Draper Laboratory in 1973) as a member of the technical staff; later he served as the director of the Control and Flight Dynamics Division, vice president of technical operations, and executive vice president. From 1990 to 1991, Dr. Fraser was deputy director of operational testing and evaluation for command, control, communications, and intelligence at the U.S. Department of Defense. He was the appointed principal deputy under secretary of defense (acquisition) from 1991 to 1993. Since 1993, Dr. Fraser has been the director of the Boston University Photonics Center and a professor of engineering and physics. His honors include the Defense Distinguished Service Medal. Dr. Fraser is a member of the NASA Advisory Council, a former member of the Aeronautics and Space Engineering Board, a former chair of three National Research Council (NRC) study groups, and a former member of six other NRC study groups.

WILLIAM C. BREEN is an expert in the area of large engineering and construction projects and a retired vice president of Fluor Daniel, where he spent 47 years with assignments in general management and project management. His assignments have included world-class projects in refining, pipelines, chemical plants, and government projects. His general management experience includes management of an engineering and construction office with a staff of 6,000; management of a European subsidiary; and serving as president of Fluor Daniel's operations at the U.S. Department of Energy's Fernald facility in Ohio. Recently, Mr. Breen has been responsible for (1) the renovation of U.S. embassies in six former Soviet republics and (2) the overall direction of Fluor Daniel's classified programs. He also served as a loaned executive to the Strategic Defense Initiative Office as special assistant to the director. Mr. Breen is a graduate of the University of Michigan. This committee is the first NRC study group on which he has served.

JOSEPH V. CHARYK, NAE, as under secretary of the Air Force, played a key role in establishment of the National Reconnaissance Office. Later he became the first president of COMSAT Corporation. In accordance with the Satellite Communications Act of 1962, he led the formation of a private corporation to develop a global satellite network. Dr. Charyk decided to make geosynchronous satellites the basis of this network. He fought skepticism that this untested technology would work for voice transmission because of a half-second time delay. He also raised funds to support this new industry and enlisted the cooperation of countries around the world. His efforts launched a global system that today serves more than hundreds of nations and billions of people. Dr. Charyk previously served on one other NRC study group.

AARON COHEN, NAE, is professor emeritus of engineering at Texas A&M University. Formerly the H.B. Zachry Professor of Engineering, he taught senior mechanical engineering design. Before teaching, Professor Cohen was an employee of the National Aeronautics and Space Administration (NASA) for more than 30 years, retiring as director of NASA's Lyndon B. Johnson Space Center. His earlier assignments included manager of the Command and Service Module in the Apollo Spacecraft Program Office, Space Shuttle Orbiter project manager, and director of research and engineering at Johnson Space Center. He also served for a year as the acting deputy administrator of NASA. Professor Cohen is a fellow of the American Astronautical Society, an honorary fellow in the American Institute of Aeronautics and Astronautics, and an honorary member of the American Society of Mechanical Engineering. He is the recipient of two NASA Exceptional Service Medals, two Outstanding Leadership Medals, and four Distinguished Service Medals. He previously served as a member of one NRC study group and as chair of two others.

RAYMOND S. COLLADAY retired as president of Lockheed Martin Astronautics. He is currently an aerospace consultant, a professor at the Colorado School of Mines, and a director on boards of several companies and organizations. Dr. Colladay's earlier positions included director of the Defense Advanced Research Projects Agency and associate administrator of NASA. He has also been a member of Defense Science Board summer studies and various other U.S. Department of Defense and NASA boards. He is a fellow of the American Institute of Aeronautics and Astronautics and of the American Astronautical Society. He earned a Ph.D. in mechanical engineering from Michigan State University and completed the advanced management program from the Harvard Business School. Dr. Colladay is a former member of the Aeronautics and Space Engineering Board and six NRC study groups, four of which he chaired.

STEVEN D. DORFMAN, NAE, is a retired vice chairman of Hughes Electronics. During his time at Hughes he served as president of Hughes Space and Communications Company, the world's leading builder of communications satellites; as CEO of Hughes Communication, a leading owner and operator of communications satellites; and as chairman of Hughes Telecommunications and Space, a unit responsible for the businesses named above plus the international development of DirecTV. After retiring from Hughes, Mr. Dorfman was the Hunsaker Visiting Professor at MIT. He has served on the boards of Hughes, Raytheon, PanAmSat, American Mobile Satellite, Galaxy Latin America, Japan Satellite Systems (JSAT), DirecTV, Galaxy Classroom, and Hughes Research Laboratories. Among Mr. Dorfman's awards are the Distinguished Public Service Award, which is NASA's highest award, and Via Satellite's Satellite Executive of the Year for 1995. He is a member of the NRC's Air Force Science and Technology Board and a former member of the Aeronautics and Space Engineering Board, three other NRC study groups, and the President's Information Technology Advisory Committee.

ELVIN R. "VALD" HEIBERG III, NAE, held leadership positions at every level within the U.S. Army Corps of Engineers during 35 years in uniform. He headed the Army's Ballistic Missile Defense Program and, in his final assignment, he commanded the Corps of Engineers. Since retiring, Lt. Gen. Heiberg has served as chief executive officer of three construction/environmental firms, and he has assisted the Coalition Provisional Authority in establishing Iraq's Ministries of

Transportation and Communications. He currently heads Heiberg Associates, which provides consulting services in engineering, environmental construction, and large-project management. Lt. Gen. Heiberg has served on the executive committee of the Transportation Research Board and six other NRC study groups and boards.

KENT KRESA, NAE, is chairman emeritus of Northrop Grumman Corporation, where he was chairman of the board of directors for 13 years, ending in 2003. During most of that time, he was also the company's president and chief executive officer. Before joining Northrop Grumman, Mr. Kresa served with the Defense Advanced Research Projects Agency, where he was responsible for broad, applied research and development programs in the tactical and strategic defense arena. From 1961 to 1968 he was associated with the MIT Lincoln Laboratory, where he worked in the areas of ballistic missile defense and reentry technology. Currently, Mr. Kresa is a senior advisor for the Carlyle Group, and he is on the boards of Avery Dennison Corporation, Eclipse Aviation, Fluor Corporation, General Motors Corporation, the California Institute of Technology, and other organizations. He is a past chairman of the board of governors of the Aerospace Industries Association, chairman of the Defense Policy Advisory Committee on Trade, and honorary fellow and past president of the American Institute of Aeronautics and Astronautics. He previously served on one other NRC study group.

LESTER L. LYLES retired from the U.S. Air Force in 2003 as commander of the Air Force Materiel Command. Prior to this assignment, Gen. Lyles served as the 27th vice chief of staff of the U.S. Air Force and, previously, as commander of the Ogden Air Logistics Center. Earlier in his career he was chief of the Avionics Division in the F-16 Systems Program Office, deputy chief of staff for requirements at the Air Force Systems Command, and director of the Medium-Launch Vehicles Program and Space-Launch Systems offices. Gen. Lyles also served as commander of the Air Force Space and Missile Systems Center and as director of the Ballistic Missile Defense Organization. He was a member of the President's Commission on Implementation of U.S. Space Exploration Policy, which released its report in June 2004. This committee is the first NRC study group on which he has served.

FRANK MARTIN has more than 29 years of experience in project management, definition, development, and operations of NASA systems for space, Earth sciences, and human space applications. He is currently the president of Martin Consulting, Inc., and chief operating officer of 4-D Systems. Previously, Dr. Martin was the program director for space systems and engineering at Lockheed Martin Space Systems, where he directed programs in space and Earth sciences, life sciences, and space exploration. Dr. Martin also has extensive NASA experience, including assignments as the assistant administrator for the Office of Space Exploration at NASA Headquarters and as the director of Space and Earth Sciences at Goddard Space Flight Center. Dr. Martin previously served on one other NRC study group.

GEORGE A. PAULIKAS retired in 1998 as executive vice president of the Aerospace Corporation, where he was responsible for the execution of the launch-readiness verification process for National Security Space System boosters and spacecraft for which Aerospace has technical responsibilities. Dr. Paulikas joined Aerospace in 1961, and he later served as director of the company's Space Physics Laboratory, vice president of Laboratory Operations, and senior vice president of the Development Group and the Programs Group. During his tenure at Aerospace, Dr. Paulikas participated in more than 150 space launches and spacecraft operations and was intimately involved in the development and flight of a number of advanced space programs critical to national security. Awards that Dr. Paulikas has received include the Aerospace Corporation's Trustees' Distinguished Achievement Award, the firm's highest honor; the U.S. Air Force (USAF) Meritorious Civilian Service Award; and the National Reconnaissance Office Gold Medal in 1998. Dr. Paulikas is a fellow of both the American Physical Society and the American Institute of Aeronautics and Astronautics. He has served as a consultant to the NASA Office of Space Sciences and the Lawrence Berkeley Laboratory, and he was a member of the executive committee of the University of California at Berkeley's Space Sciences Laboratory. Dr. Paulikas has served on the USAF Scientific Advisory Board (twice) and the Los Alamos National Laboratory Physics Division Advisory Committee. He has a Ph.D. in physics from the University of California at Berkeley. He is currently the vice chair of the NRC's Space Studies Board and has previously served on 11 NRC study groups.

JOHN B. PELLER is a consultant who retired from the Boeing Company as a vice president and program manager for ground-based midcourse defense. In that role, he was responsible for Boeing's work as the lead systems integrator for the National Missile Defense Program. His first task was to assemble what had been a piecemeal Pentagon research and development effort into a single, major acquisitions program. He also created the Boeing approach to executing the lead systems integrator role on the U.S. Army's Future Combat System Program, one of the largest systems integration projects in the nation. Dr. Peller also has extensive experience in the Minuteman missile and space shuttle programs. He has served on the Air Force Scientific Advisory Board and is a fellow of the American Institute of Aeronautics and Astronautics. He has a Ph.D. from the University of California at Los Angeles. This committee is the first NRC study group on which Dr. Peller has served.

HARRIS M. "BUD" SCHURMEIER, NAE, retired from the Jet Propulsion Laboratory (JPL) as the associate director after a 36-year career with the JPL. During that time he held technical and management positions that encompassed a broad spectrum of technical disciplines and management responsibilities. At the start of the space program at JPL, he developed the concept and organization of the Systems Division to handle the multidiscipline systems engineering activities associated with the design and development of autonomous spacecraft and the conduct of planetary spaceflight missions. Mr. Schurmeier managed several multi-hundred-million-dollar projects at JPL that sent robotic spacecraft to explore the Moon and planets. As the first project manager of the Voyager Project, he directed the design of the mission and the development of the spacecraft. He served on the NASA Research Committee on Manned Space Flight, the Research Advisory Committee on Missile and Space Vehicle Aerodynamics, the Apollo 13 Failure Investigation Team, and the Hubble Space Telescope Repair Mission Review Board. Mr. Schurmeier chaired review boards for the Galileo Project and the Keck Observatory Project for 10 years after retiring from JPL in 1985. He now works with the Planetary Society on its Solar Sail Demonstration Project. This committee is the first NRC study group on which Mr. Schurmeier has served.

ROBERT C. SEAMANS, JR., has held a variety of senior positions in the aerospace community, including the following: director of the Flight Control Laboratory at MIT, chief engineer of RCA's Missile Electronics and Controls Division, national delegate to NATO's Advisory Group for Aerospace Research and Development, associate administrator and deputy administrator of NASA, secretary of the Air Force, president of the National Academy of Engineering, the first administrator of the Energy Research and Development Administration, dean of MIT's School of

Engineering, and chair of the board of trustees of the Aerospace Corporation. Dr. Seamans has previously served on two other NRC study groups, including one that he chaired.

JOHN K. WELCH retired from General Dynamics as executive vice president of the Marine Systems Group, which included Bath Iron Works, Electric Boat, National Steel and Shipbuilding Company (NASSCO), and American Overseas Marine (AMSEA). He is currently a private consultant to government and industry. Mr. Welch joined General Dynamics in 1989 as Electric Boat's vice president for program development, overseeing its strategic planning and competitive analysis, program and product marketing, and high-technology program acquisition and management. He then was vice president of programs with responsibility for new construction programs (Seawolf-, Ohio-, and Los Angeles-class ships). He also was the initial program manager for the new Virginia-class attack submarine. He later became president of Electric Boat. Mr. Welch has an M.S. in aeronautical engineering from the Naval Postgraduate School, an M.B.A. from Loyola College, and a B.S. in aerospace engineering from the U.S. Naval Academy. He serves as a director for the Battelle Memorial Institute, the Naval Submarine League, and the Naval Academy Foundation and is a trustee of Bryant College and Webb Institute. This committee is the first NRC study group on which Mr. Welch has served.

F. GORDON WILLIS is a consultant in systems engineering and design automation. From 1999 to March 2004, he was president and chief executive officer of VulcanWorks, a company that provided software and services for systems engineering, dramatically reducing the time and cost of product development. The company was recently sold to Trilogy Software. Mr. Willis retired from Ford Motor Company in 1999 after 23 years of service, during which he held a variety of positions in both computer systems and product engineering. From 1992 to 1999, these included chief engineer for automatic transmission engineering, chief engineer for vehicle engineering (Europe), and chief engineer for chassis. From 1989 to 1992, he was director of product and manufacturing systems, and prior to that held a variety of positions in powertrain control development and computer-based simulation of vehicle performance. Mr. Willis has B.S. and M.S. degrees in mechanical engineering from MIT, and an M.B.A. in operations research from the University of Michigan. Mr. Willis has previously served on two other NRC study groups.

A. THOMAS YOUNG, NAE, is a retired executive vice president of Lockheed Martin Corporation. Mr. Young previously was president and chief operating officer of Martin Marietta Corporation. Prior to joining industry he worked for 21 years at NASA. There he directed the Goddard Space Flight Center, was deputy director of the Ames Research Center, directed the Planetary Program in the Office of Space Science at NASA Headquarters, and was mission director of the Project Viking Mars landing program. Mr. Young was a member of the NASA Advisory Council and six NRC study groups, two of which he chaired.

Attachment C

Program Briefings

As part of the information-gathering effort for this study, five committee members made presentations to the committee on lessons learned from systems integration of past space and nonspace megaprograms, as follows:

- aerospace programs from Viking to Space Station, A. Thomas Young
- Apollo/Bellcom, Robert C. Seamans, Jr.
- National Reconnaissance Office/COMSAT, Joseph V. Charyk
- selected megaprojects from the U.S. Army Corps of Engineers, Elvin R. “Vald” Heiberg III
- selected civilian mega-projects, William C. Breen

These programs were selected because they exhibited systems integration characteristics comparable to those of Project Constellation in terms of program scope and complexity.

Attachment D

Systems Integration Tasks

The Office of Exploration Systems has defined Project Constellation in terms of six tiers:

- Tier 1. Enterprise Elements: Project Constellation (a system of systems)
- Tier 2. System (e.g., crew transport system, surface systems)
- Tier 3. Segment (e.g., crew exploration vehicle, launch vehicle, ground segment)
- Tier 4. Element (e.g., booster element)
- Tier 5. Subsystem (e.g., booster main engine)
- Tier 6. Assembly (e.g., thrust chamber assembly)

Listed below are the types of tasks that the committee believes should be included in systems integration at Tiers 1 and 2.

TIER 1: ENTERPRISE ELEMENTS / SYSTEM OF SYSTEMS

At Tier 1, the systems integrator would accomplish tasks such as the following:

- refinement of Tier 1 performance requirements
- drafting of verification and validation requirements and plans for Tier 1 requirements
- completion of system-of-systems architectural trade studies leading to refined Tier 1 (system of systems) architectures and concepts of operation, including—
    - top-level operational sequences of operations
    - operational block diagrams (for each operational phase)
    - system-of-systems block diagrams (for each operational phase)
    - information architecture
- definition of other top-level requirements across a system of systems, such as redundancy, reliability, and availability
- flowdown of system of systems performance requirements to Tier 2 systems—
    - crew transport
    - cargo transport
    - surface systems
    - in-space systems
    - ground systems
    - robotic precursors
- development of functional interface specifications for Tier 2 systems
- drafting of verification and validation requirements and approaches for Tier 2 systems
- refinement of program approach and phasing at the Tier 1 level
- establishment, operation, and support of other critical systems integration functions, such as:

- configuration management and control (including Tier 1 Change Control Board)
- mission assurance and safety including Tier 1 failure mode and effects analysis (FMEA)
- Tier 1 risk analysis and risk reduction programs

- maintenance and rebalancing of the efforts listed above as required

Completing these tasks will require at least the following inputs:

- Project Constellation vision
- Project Constellation top-level requirements (system of systems)
- preliminary system-of-systems architectures developed by NASA
- preliminary program approach and phasing developed by NASA

TIER 2: SYSTEMS

At Tier 2, the systems integrator would accomplish tasks such as the following:

- refinement of Tier 2 performance requirements
- drafting of verification and validation requirements and plans for Tier 2 requirements
- completion of architectural trade studies leading to refined architectures for each Tier 2 system (Tier 2 expansions of Tier 1 architectural products)
- definition of other Tier 2 level requirements, such as redundancy, reliability, and availability
- flowdown of Tier 2 performance requirements to Tier 3 (Segment), such as the following in the crew transport system:
    - crew exploration vehicle
    - launch vehicle
    - extravehicular activity systems
    - intravehicular activity systems
    - in-space transport systems
- development of interface specifications for Tier 3 systems
- drafting of verification and validation requirements and plans for Tier 3 requirements
- refinement of program approach and phasing for Tier 2
- establishment, operation, and support of other critical systems-integration functions, such as:
    - configuration management and control (including Tier 2 Change Control Board)
    - mission assurance and safety, including Tier 2 FMEA
    - Tier 2 risk analysis and risk reduction programs
- maintenance and rebalancing of the efforts listed above as required

Completing these tasks will require at least the following inputs:

- Tier 1 outputs
- Tier 2 program constraints from NASA

Attachment E

Optional Tasks

The statement of task (Attachment A) includes three tasks that the committee was directed to address only if time permitted. Because of the limited time available, the committee focused on the primary tasks, and it had little time to address the optional tasks. These tasks and the committee's responses appear below.

- "*The committee should define metrics that could be used to measure progress of the systems integration activity.*" The committee did not have time to address this issue.
- "*In completing this task, the committee should evaluate the scope of the Project Constellation systems integration function, as defined by NASA. What part of the scope, such as approval of interface requirements, should remain a government function, regardless of which systems integration approach may be selected?*" Regardless of the systems integration approach selected, systems integration tasks related to the areas below (among others) should remain a government function:

    - accident investigations
    - approval of cross-contract system interfaces
    - astronaut selection, training, and certification
    - handling of extraterrestrial material (lunar and martian)
    - high-level requirements definition
    - interactions with other federal agencies
    - international interfaces and agreements
    - launch approval
    - operations
    - planetary protection and quarantine
    - relations with the public, the Administration, and the Congress
    - safety
    - space medical and health issues
    - top-level budget authority
    - use of nuclear material (in partnership with the Department of Energy)
        - radioisotope thermal generators
        - reactors

- "*What specific skills, if any, should be subcontracted back to the government if the systems integrator is not a government organization?*" If the government is not the systems integrator, subcontracting work back to the government would increase the number of interfaces that would have to be managed. Therefore, rather than subcontracting work back to the government, it would be better for the government to reduce the scope of work of the nongovernmental systems integrator. Tasks that the government should retain are included in the list above.

Attachment F

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Dwight Abbott, Aerospace Corporation (retired)
Alexander H. Flax, NAE, Consultant
Angelo "Gus" Guastaferro, Lockheed Martin Missiles and Space Company (retired)
Richard Kline, Klintech, LLC
Robert Monroe, Vice Admiral, U.S. Navy (retired)
James Odom, Science Applications International Corporation (retired)
Emery Reeves, NAE, U.S. Air Force Academy (retired)

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert A. Frosch, NAE, Harvard University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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