LESSONS LEARNED REPORT OF

Commercial Orbital
Transportation Services
(COTS)
Commercial Orbital Transportation Services (COTS)
Lessons Learned for Commercial Capability Development Partnerships

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Human Exploration & Operations
Mission Directorate Chief Knowledge Officer

HEOMD Commercial Spaceflight Development Division
Foreword / Approval

This report has been developed by the National Aeronautics and Space Administration (NASA) Chief Knowledge Officer (CKO) and the Human Exploration and Operations Mission Directorate (HEOMD) Knowledge Services Management team in close coordination with the Commercial Spaceflight Development Division in support of ongoing and future NASA commercial capability development partnerships.

Signed
Patrick Johnson
HEOMD Chief Knowledge Officer

Signed
Phil McAlister
Director, Commercial Spaceflight Development Division
Executive Summary

The ultimate goal of the Chief Knowledge Officer (CKO) is to provide the NASA workforce ways to find and use the critical knowledge required now and in the future to achieve mission success in a highly complex and unforgiving environment. The overall importance of critical knowledge capture and transfer has been articulated in recent recommendations to NASA by the Aerospace Safety Advisory Panel (ASAP) and has been specifically identified in NASA authorization legislation.

The Commercial Orbital Transportation Services (COTS) Program provides a starting point for formulation, design, management and implementation of future public-private capability development partnerships. This report and the associated web-based resources are intended to assist in the early discussions for future commercial capability development partnerships to stimulate thinking and raise questions that need to be addressed in concept development, planning and implementation phases. Each lesson learned is accompanied by a corresponding application to future capability development partnership programs.

For the purposes of this task, Critical Knowledge (CK) is defined as broadly applicable lessons learned that enable mission success, stimulate critical thinking, and help raise questions that need to be addressed at various phases in a project life cycle. CK is considered to have potential utility for future programs, projects and partnerships.

Lessons were acquired through audio and video interviews with current and former COTS Program stakeholders and participants, including the NASA stakeholders, Orbital ATK, and SpaceX Corporation. However, this report only includes the lessons from NASA stakeholders, totaling over 140 individual, documented lessons.

The NASA COTS Program lessons have been organized using a five-element framework: (1) creating the environment for innovation, (2) planning and acquisition, (3) managing the funded Space Act Agreement (SAA), (4) supporting the partner, and (5) operating in the space station environment.

Key lesson abstracts derived from interviews have been summarized in a fishbone diagram (Figure 3).

**NASA:** Important lessons (success factors) for NASA included: (1) shift of incentives and risk by employing a milestone-based SAA approach, (2) collaborative management partnership approach, (3) establishment of high-level functional requirements allowing freedom to innovate on the design solution, (4) a willingness to negotiate the method of demonstrating compliance with requirements, (5) a consolidated ISS requirements book (SSP 50808), (6) a light-touch oversight surveillance approach, (7) the COTS Assistance Team (CAT), and (8) the system safety hazards analysis process and Safety Review Panel – influencing design and capabilities of the commercial partners’ vehicles.

These documented lessons are complemented by over 150 individual video clips based on video interviews and available via three cross-linked, web locations: (1) the Knowledge @ NASA YouTube channel, (2) the COTS Critical Knowledge website, and (3) the NASA Critical Knowledge Gateway.
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Part I. Introduction

Goals and Objectives / Critical Knowledge Capture
This report is a collaboration between the Chief Knowledge Officer (CKO) and the Human Exploration and Operations Mission Directorate (HEOMD) to capture and transfer knowledge critical to current and future mission success. NASA recognizes the importance and necessity of this high visibility task designed, in part, to specifically address the 2011 Aerospace Safety Advisory Panel (ASAP) recommendations that NASA improve capture, transfer and integration of critical knowledge and lessons learned. The COTS Program implementation case provides a template for future public-private partnership capability development activities.

Critical Knowledge
For the purposes of this task, Critical Knowledge (CK) is defined as broadly applicable lessons learned that enable safety and mission success. CK is considered to have potential utility for future NASA programs and projects as well as commercial partnerships designed to develop new capabilities that support agency goals and objectives. CK is best communicated and characterized with a verb or action statement. CK is tightly connected to individual roles, responsibilities and work processes. CK has a temporal or time-indexed characteristic spanning a project life cycle featuring many CK actions correlated with early, up-front program formulation and planning activities.

CK lessons learned (LL) can be derived from all stakeholders within a program or project, which may include program management; supporting engineering, safety and functional subject matter experts (legal, procurement and environmental management); contractors; and/or commercial partners.

CK examples include:
- Know what: critical requirements, critical questions that need to be addressed at various phases in a project life cycle
- Know how: critical processes
- Know when: critical decision points, critical reviews

CK can include managing approach and style, such as defining expectations, values, areas of emphasis such as quality, or openness to innovation. CK can also include managing people or communication strategy. The breadth and depth of the “CK domain” is reflected in the following discussion of the CK organization and indexing approach.
Individual CK Lesson Format
Each individual Critical Knowledge lesson contains: (1) a descriptive, tagline title, (2) a narrative paragraph providing context, and (3) an “Application to Future Capability Development Partnerships” mini-paragraph leading with a verb or action statement. An example from the International Space Station Knowledge Capture is shown below:

Lessons: Vehicle Design – Maintenance
“The ISS design required huge support from ground.” The design should not require 27 people in a control room monitoring telemetry for relatively simple repair or maintenance tasks. The need exists to move toward a paradigm where ground control is conducting strategic analysis and monitoring while the crew is performing tactical functions without extensive supervision.

Application to Exploration: Design for maintainability concepts must be incorporated in architectural studies to ensure design of an efficient and operable deep space crewed vehicle.

Companion Web-based Resources
This report has companion video content available via three cross-linked web locations:
- Knowledge @ NASA YouTube Channel
- COTS Critical Knowledge Website
- CK Gateway

Knowledge @ NASA YouTube Channel
Over 150 individual video clips have been created based on interviews with personnel from NASA, Orbital ATK, and SpaceX. The video segments are partitioned into playlists by program, discipline and person. Each video is also meta-tagged with topically relevant key words to allow for additional search functionality for the user.

Once the user selects a video, a playlist containing additional videos from the respective interviewee appears on the right side. A short description and link to the respective lessons learned module is located below the interviewee’s name and title of the video. Knowledge @ NASA
The YouTube platform allows for accessible and searchable videos, but it also allows for tracking analytics. Not only are views tracked, but retention time, demographics and source traffic are all tracked using the platform. This allows for a better understanding of topical interests and how users consume content.

**COTS Critical Knowledge Website**
The module incorporates an introductory video, and links to video interviews with key COTS participants as well as documents and links. The module is deployed utilizing NASA’s Content Management System (CMS) and YouTube for hosting the video interviews. [COTS Lessons Learned Page](#)

**Critical Knowledge Gateway**
The Critical Knowledge Gateway (CK Gateway) is housed within the NASA CKO website, and its primary purpose is to improve capture, transfer and integration of critical knowledge and lessons learned. The Critical Knowledge Gateway, which is hosted on km.nasa.gov, allows users to search the video interviews using multiple filters, including thematic discipline, program and keywords. The CK Gateway user interface design provides access to information via search, browse and filter functionality. A keyword search function is available at the top left-hand side of the screen. [Critical Knowledge Gateway](#)

**Browse/Filter:** Once a user selects an icon on the home page, they are routed to the results page, where additional filters are made available to further narrow down content options. The results page has a left-hand filter navigation area with results populating across the center and right-hand portions of the screen. The filters include: (1) Disciplines (2) Critical Knowledge Framework, (3) Project Lifecycle Phase, and (4) Program/Project. Multiple filters may be selected within all filter categories.

Once a user selects the desired filter options, the accompanying results (video clips) are populated dynamically in the designated frame on the center and right side of the screen. The results are pulled in from the Knowledge @ NASA YouTube channel, a NASA-approved channel that hosts Critical Knowledge content.

**Module/Browse:** The user also has the option to go directly to a specific program or project CK website (e.g., ISS, ARES I-X or DART) with access to video content as well as public domain documentation.
Part II. Lessons Learned

NASA LL Introduction
This section contains the following sub-chapters:

- Creating the Innovation Environment
- Planning and Acquisition
- Managing the Funded Space Act Agreement
- Supporting Commercial Partners
- Operating in the ISS Environment

Additional indenture, when appropriate or necessary, is discussed at the beginning of each sub-chapter. Lessons learned -- derived from audio and video interviews -- have been organized into the major areas shown below in Figure 3, a synoptic graphical map (one pager). While not all-inclusive, the graphic identifies key CK themes emergent in the interviews.

Figure 3. Critical Knowledge Fishbone – NASA COTS Implementation
Creating the Innovation Environment

LESSON: Secure Senior Leadership Support - 1
“Senior leaders must be talking the talk [but many] other factors come into play of success. The more resistance you encounter the more support you will need.” NASA Administrator Mike Griffin carved out $500 million for the COTS initiative and publicly promoted the idea, but putting the right team in place and selecting the right partner(s) was instrumental in making COTS a success. Application: Top-level support is essential for program success, but technical progress and demonstration of “early wins” is necessary to maintain momentum.

LESSON: Secure Senior Leadership Support - 2
Administrator Mike Griffin was a lead advocate for the COTS concept, and he publicly supported the program with a substantial five-year, $500 million investment. It was sizeable enough to reasonably achieve program goals, but was small enough [as compared to NASA’s larger program budgets] to stay off the radar during development. Application: For a new venture to succeed, you need buy-in from the top of the organization at a minimum. Additional legitimacy placed on the program through investment or other means is also a necessary component for success.

LESSON: Select the Right People
The COTS program management team noted the importance of creating the right environment for an FSAA project to succeed. The project contained multiple elements, including institutional strategic alignment, management culture, internal and external political support, and shared economic incentives. Application: Early formulation and project planning must affirm senior management support and carefully select the project leadership and management team.

LESSON: Create “Room to Breathe”
In order to innovate, it is necessary to be separate from the larger organization to allow for agile development, flexibility and tactical decision-making. COTS was reported in status meetings as a side note to deflect attention. With other major programs in operation (space shuttle) and development (Constellation), COTS was treated and messaged as a side bet. Over time, the program began to receive gradual recognition until 2010 when SpaceX and Orbital successfully berthed to ISS”. The SpaceX Dragon first berthed with the ISS in 2012. The Orbital Cygnus first berthed with the ISS in 2013. Application: When embarking on a new development venture with nontraditional processes, the new organization must be treated as an independent, stand-alone entity. To promote innovation and change, the new organization must be allowed to develop its own new culture without being forced to inherit the legacy policies or procedures for conducting business.

LESSON: Give Commercial Companies Enough Leeway to Do What They Do Best
By allowing a commercial company to follow its own best practices and procedures that have worked in other applications, the company will be afforded the opportunity to tailor a Space Act Agreement set of
objectives. In addition, this approach can be instrumental in building the initial trust that the company is the subject matter expert in certain areas. Those same strengths should, in theory, be the reason why they were selected to be a partner.

Application: Any time a company has a commercial market share the government should allow the commercial partner to leverage existing best practices, procedures, etc. to find efficiencies for a government application.

**LESSON: Communicate the Message - It’s OK to Fail**

Iterative design, test, redesign and re-test is a fundamental design development philosophy and approach that expose and remove latent defects in the design. Test failure is viewed as a natural occurrence in the DDT&E process and should be expected in FSAA’s designed to develop any new capability. “The companies were allowed to fail. You have to have things fail to learn new lessons. Sometimes projects are over engineered. People become afraid of failures.”

Application: FSAA program managers should embrace and accept intelligent failures (those not resulting from negligence) as part of the capability development process and assist in defining expectations with internal and external stakeholders.

**LESSON: Bounce Back from Failure**

Space exploration is hard and unforgiving, and demands perfection, especially during the high power (high energy transfer) launch phase required to climb out of Earth’s gravity well. The key lesson is to recognize the risks and do your best. When you fail, fix the problem, learn from the failure, and return to flight with an improved space system.

Application: Capability development activities must be undertaken within an environment where failure is recognized as a possibility and failing forward is the goal. The NASA sponsors and SAA project managers should create an environment where it’s OK to fail and at the same time ensure that lessons are learned and the activity is indeed “failing forward.”

**LESSON: Don’t Let Entrenched Culture Kill a New Product**

Cultural inertia is something to be aware of when trying to accomplish a task in a new way. It is critically important to recognize that cultural norms may be a barrier to innovation. “If you take a culture that developed a very successful product and use that culture to develop a new product you are 100% guaranteed to kill that new product.... In order to be successful you have to take it out of corporate structure. Give it its own money and let it develop its own culture.”

Application: As NASA moves forward with capability development partnerships through funded Space Act Agreements, it is important to consider how established oversight and due diligence processes may work against efforts to stimulate innovation.

**LESSON: Help Partners Succeed**

NASA created an ecosystem to help commercial partners survive. Agency representatives met with insurance companies, the FAA and Wall Street investors to raise awareness of the commitment NASA has in commercial space and to demonstrate the benefits of working in microgravity. "We did a lot of
things. We went to Wall Street to talk to the investment community to stand by Kistler and help investors understand the government was planning to invest a lot of money in these companies.”

Application: A Space Act Agreement partnership should go beyond just executing the scope of work in the agreement. The government should help create a commercial market outside of NASA.

Planning and Acquisition

Introduction

The Planning and Acquisition chapter has been subdivided into the following subsections:

- Strategic Planning
- Legal & Acquisition
- Evaluation of SAA Applicant Proposals
- Milestone Criteria Development & Definition

Strategic Planning

LESSON: Establish Clear Goals and Objectives

Much time and rigorous thought must be placed on establishing the right goals and objectives. Lay out a minimalistic set of goals and objectives and allow industry to offer up their best innovative ideas. All “firm” requirements should be scrutinized; requirements necessitate verification, and verification increases project cost.

Application: In pre-formulation of a new project, managers should minimize requirements and maximize flexibility. Requirements stifle innovation and restrict industry partners from developing creative solutions. However, clear goals and objectives focus on “what” is needed at the end, rather than managing “how” it is developed throughout the process.

LESSON: BENCHMARK – 1

Don’t be afraid to bring in outside expertise. NASA has been a national leader in technical, engineering expertise for 50 years, but was lacking in the business and investing nuances that the funded SAA introduced. COTS management hired a venture capitalist to support the team throughout the formulation, evaluation and selection processes to ensure that the business aspects were adequately understood and considered. The COTS team became well-versed in learning how to read, write and evaluate business plans -- key elements in any SAA proposal.

Application: Be humble enough to bring in a subject matter expert when presented with unfamiliar workplace situations.

LESSON: BENCHMARK-2

Knowledge transfer is pivotal in early formulation. COTS participants shared their efforts to transfer knowledge to the Commercial Crew Program at KSC. Cargo and crew personnel held face-to-face knowledge sharing meetings to transfer their lessons and best practices. In addition, a second meeting was held with private sector consultants to discuss non-NASA, broader industry goals for low Earth orbit space travel. Lastly, five Evolved Expendable Launch Vehicle (EELV) representatives from DoD shared
their experiences from a similar capability development project. This early knowledge transfer aided the Commercial Crew Program as it established the organization, policies and procedures.

*Application: Focused front-end planning is essential for project success. To reap the benefits of experience from previous program managers, it is prudent to derive corporate knowledge, lessons and best practices from available subject matter experts. The knowledge sharing forum is a useful method to align an organization’s goals, roles and expectations.*

**LESSON: Verify Potential Commercial Partner Capabilities**

Structure the partnership around existing technology and attainable goals. COTS was more successful than previous public-private partnership attempts (such as X-33) because COTS goals and objectives were more attainable by industry, whereas previous PPPs required too far of a technological reach, asking for a development in uncharted territory. Conversely, transporting cargo and crew to LEO had been demonstrated and adequate industry knowledge existed to develop this capability through a government-industry partnership.

*Application: The government should take on the cutting-edge, technological advancements where markets aren’t currently developed and mature those technologies to the point where industry can drive down costs and establish a profitable operation.*

**LESSON: Require Relatively Mature Technology**

Funded Space Act Agreements have the potential to carry products or services from a state of high technology maturity to viable commercial offerings. Discussions with multiple interviewees highlighted the importance of engaging partners with relatively mature and proven technology.

*Application: The viability of a partner must be demonstrated in both financial as well as technical readiness. Funded SAA source selection teams must ensure that technology reach is not inconsistent with the goals of the capability development effort.*

**LESSON: Evaluate Potential Commercial Market**

Because the conditions were right, the government was able to make a modest investment of $800 million to establish two medium launch vehicles and two autonomous vehicles that can berth with the ISS. “The question is when to use these partnership methods. If the need is unique to NASA then a partnership does not make sense. This partnership type scenario is useful when the product may be of commercial value as well. As with the case of COTS, Mike Griffin realized that there might be others who could make use of low earth orbit cargo services. Instead of buying a system he thought let’s buy a service. If the service is not available then what can we do to make this happen?”

*Application: Prior to determining acquisition strategy, a program manager should assess the market conditions to see if an item can be purchased off the shelf or through Space Act Agreement partnership or traditional government procurement process.*

**LESSON: Build in a Carrot**

A guaranteed flight manifest -- with a sweet spot of six to eight flights -- enables cost effectiveness by allowing companies to engage in bulk purchases of components and spares. Developing a long-term
commitment keeps the price down and mitigates schedule delays by having a continuous production flow. “Certainly having a task order for eight (CRS) missions gave us and our board of directors’ confidence to handle cost increases and schedule delays.” Use a two-phased acquisition approach that (1) provides seed funding to develop and mature capabilities for future NASA purchase, and (2) enables FAR Part 12 procurement where NASA engages in a contract for a defined amount of goods and services over a set time period, serving as incentive to industry partners to participate in the initial capability development phase because the FAR provides a defined return on investment from capital spent during Phase 1. With COTS the follow-on CRS contract was important since it was the means for private companies to get their ROI and enabled them to begin production earlier and enhance system capabilities by investing their own money. A critical success factor in COTS SAA implementation was the potential for a substantial commercial contract downstream, and interviewees stressed the need to recognize commercial shareholder goals and risk posture, which drive their willingness to invest in a capability development partnership.

**Application:** The planning and acquisition strategy for any specific NASA funded capability development activity should articulate the win-win, describing potential investment payback opportunities and also addressing the topic of intellectual property retention. Issuing a Space Act Agreement should accompany a production/service contract to achieve the best financial leverage for a long-term project.

**LESSON: Flight Planning Transition from COTS to CRS**
Because the time separation between the capability development demonstration flight and the first production mission was kept long enough it was possible to implement lessons learned.

**Application:** Keep a reasonable spacing between the first two missions allowing for lessons learned to be implemented and verified.

**LESSON: Pick Two Partners**
Employ a dual-path risk management approach. It was critical to have two companies develop two dissimilar systems, creating system level channelization, e.g., multiple channels providing certain functions for fault tolerance, reliability and confidence in actually having those functions. Relying on one system can become problematic if you encounter a serious, unexpected problem. Such problems, like a launch vehicle failure, can demand a serious response, even shutting down the system for years. Such a problem would be devastating to a logistical program, such as resupplying the ISS or station/base elsewhere. Furthermore, competition brings out the best in the companies and avoids a “this is good enough” mentality by having a benchmark to be measured against. This resulted in better products and services at a better price.

**Application:** Use channelization at the system level. Have multiple systems (channels) provide key services (functions) to get system-level fault tolerance and reliability. Having two systems providing logistical support gives you confidence that your needs are being satisfied.

**LESSON: Mitigate Risk with Multiple Providers**
Anticipate the failure of a partner. Start with a large base of partners and down select the group as the capability development activity progresses. Establish criteria for down selecting early on to ensure
development of robust requirements and minimize risk associated with contract protests. When RpK was terminated, the acquisition documentation was quickly and easily used to conduct a second competition, which resulted in the on-ramping of a new commercial partner, Orbital ATK.

Application: Have plans in place in case a commercial partner is terminated at any point in the SAA execution. Different phases will have different responses. If the termination occurs early enough, then the remaining funds can easily be used for a new partner via a second-round acquisition. If a termination occurs later in the SAA execution process, then the remaining funds can be used to augment the efforts of the remaining partners.

LESSON: Create a Win-Win
A successful commercial/NASA partnership needs to have an area of overlapping interest wherein value is obtained for both the government and the commercial shareholders. Ensure alignment of goals before you establish a partnership. Throughout the announcement, evaluation, and selection phases of the acquisition process, the agency must ensure that NASA and industry partner goals are tightly interwoven. Ensure equivalent investment and equivalent returns. With COTS, both NASA and the partners invested a similar amount of money and resources, and therefore stood to gain or lose a similar amount of ventured capital. Government and commercial partners eventually gained a similar amount of benefits: NASA had two inexpensive, demonstrated systems/channels for delivering and removing cargo from the ISS, while the commercial partners had a steady, long-term contract and associated revenues to provide the service.

Application: The only way for a partnership to succeed is to begin the project with the same end goals in mind. This allows for flexibility as the means to the end may change during the project development cycle. Partnerships work best when both partners are expected to invest equivalent amounts and expect equivalent returns.

LESSON: Plan Program Reserve to Mitigate Risks
All partners assumed that the funds that were made available originally by the government were all that would be available. At some point additional funds were made available as part of a government augmentation funding. These additional funds were useful in adding scope to mitigate risks not previously anticipated. Early on, it is difficult to anticipate in which areas issues may arise, and providers may feel that there are certain tests that are not necessary. Once fabrication and assembly begin, unforeseen risks emerge that need to be mitigated. The augmentation funding allowed the commercial partners to drive down risk through increased thermal vacuum testing, electromagnetic interference (EMI) testing, and rendezvous and docking demonstration. “In the case of the EMI testing, that test showed a lot of susceptibility to critical rendezvous and proximity operations equipment in the EMI environment. We would not have discovered that until the demonstration flight and the demonstration flight would have been unsuccessful. That test was really worth its weight and cost; it exposed real weaknesses that required engineering solutions.”

Application: It can be useful for the NASA program office to hold a set of funds back to be tapped once the partners have made substantial progress. These funds should be used to buy down residual risks as demonstration nears instead of gradually tapping into the reserve. If they are deployed too early, the
commercial partners may not know the ideal place to use them. If the funds are deployed too late, there may not be enough time to properly utilize them in the program flow.

LESSON: Link the Space Act Agreement to STEM Objectives
Orbital ATK managers discussed how the cargo resupply missions stimulated excitement and interest within local communities and across the mid-Atlantic region. Of special note was the inspirational effect on STEM education by providing opportunities for student payloads to fly on Cygnus (and/or SpaceX Dragon).
Application: The potential for STEM activities and/or participation should be explored as part of the early concept planning for future Space Act Agreements.

LESSON: Surveillance Advantage with Self-governing SAA
A key aspect of the free-market strategy was to have the commercial partners self-govern. They were highly incentivized to meet SAA milestones and manage efficiently and effectively.
Application: Self-governing commercial partners save the government sponsor time and resources typically devoted to surveillance and monitoring.

Legal and Acquisition
LESSON: Engage Legal and Procurement Stakeholders from the Beginning
When searching for alternative acquisition approaches the COTS team engaged the legal and procurement communities early on. Once acquisition goals and objectives were clearly defined, legal and procurement determined that a Space Act Agreement, which had been around since 1958, could be utilized similarly to the Other Transactional Authority (OTA) acquisition vehicle the Department of Defense uses. While SAAs are commonly used for partnerships at NASA, this was the first time the Space Act Agreement was used as a significantly funded acquisition instrument.
Application: When planning a new acquisition, engage the legal and procurement staffs early on and clearly articulate the goals and objectives for the acquisition vehicle.

LESSON: Evaluate All Available Acquisition Methods
The COTS FSAA was compared to the traditional Cost-Plus Fixed-Fee (CPFF) approach as a viable alternative. CPFF contracting was described as a vestige from government World War II contracting and a method that offers no incentives to control cost or meet schedule. The lack of such incentives (along with endless government contract changes) conspires to stretch timelines and balloon the costs of maintaining a standing army of contractors. The FSAA approach with milestone-based payments was described as more like a Firm Fixed-Price (FFP) contract where more performance risk shifts from the government to the contractor.
Application: NASA senior management, program, project and technology development managers should be offered formal training in acquisition management alternatives, where FAR, NASA FAR Supplement, Space Act Agreements, legal, procurement, programmatic issues, alternatives, pros and cons are discussed.
LESSON: Ensure the SAA is the Right Approach-1
When assessing appropriate procurement or acquisition strategies, a manager should start with a clear vision of the project’s goals and objectives. This should begin with the end in mind and be able to answer the question of “What do I want to accomplish with this project?” From there, the following questions should be considered:

- Does the project goal fulfill a NASA need, requiring the procurement for goods or services?
  - Or is the intent to promote capability and technology development?
- Does NASA need to retain the intellectual property, rights to data, and rights to invention?
  - Or is NASA willing to waive those rights to stimulate commercial sales?
- Is NASA the only customer for the capability?
  - Or is there a market for the capability or technology outside of NASA?
- Is the technology development cutting-edge?
  - Or is the technology well understood, making the industry capable of accomplishing?

Application: From a managerial perspective, funded SAAs are only appropriate if NASA is interested in maturing a technology for the stimulation of the U.S. commercial space industry, forfeiting the right to intellectual property. From a technical readiness perspective, the funded, Space Act Agreement legal instrument is appropriate when industry capability is almost there and the government can invest (human capital and funding) in that capability to make it available to a broader customer base.

LESSON: Ensure the SAA is the Right Approach-2
Prepare to address a potential protest by ensuring the project is well aligned with agency goals. “We knew the agency had a piece of its legislation that said we were to seek and encourage commercial developments in space. We wanted to do something in furtherance of that goal. The administrator [set aside] $500 million to see if someone could develop the capability. We had to make this very clear. If there was an exact [NASA] need and a deliverable that was needed, we would have had to use a procurement contract. With GAO protests, the ability to have the documentation in place to show what we wanted to do and why the other instruments wouldn’t fit was crucial. We documented everything.”

Application: Protests commonly occur following the award of large contracts, so NASA should plan accordingly by carefully documenting rationale, decisions and selection criteria.
LESSON: Allow Commercial Partners to Retain Intellectual Property Rights

One participant contributed the following: “We looked at procurements, grants, cooperative agreements, and the funded SAA. The funded SAA had never been used this way. I think primarily because intellectual property was an issue we went with an SAA. This allowed the company to seek commercial customers. NASA would not be the sole customer.”

Application: When engaging in a public-private partnership, it can be important for the commercial partner to retain ownership of the products and be able to sell to a broader market. In this case, forfeiting the government’s rights to intellectual property was a key component of establishing the PPP.

LESSON: Communicate Clear Rules within the SAA

It is essential to establish trust with partners, in part through narrowly bounding termination events. Termination was limited to specific, important instances to prevent mistrust, uncertainty and pressure between NASA and its partners. The only circumstances that allowed for termination were:

1. Congressional funding is zeroed out
2. Partner’s failure to make progress toward meeting a milestone
3. Mutually agreed termination

This straightforward, transparent approach set the foundation for a healthy public-private partnership. Industry partners understood that NASA was investing in them to accomplish the negotiated milestones, and as long as they were making technical progress toward accomplishing milestones, there was no worry for termination. Only in the event of continual missed milestones or stagnated technical progress would the termination option be exercised.
Application: When entering a partnership, it is essential to clearly define exit criteria in addition to each party’s roles and responsibilities. This approach minimizes uncertainty and distrust, while clearly defining the steps (milestones) required for success.

LESSON: Establish a Change Control Process within the Space Act Agreement
The COTS activity was funded through a fixed price Space Act Agreement. The acquisition method provided no mechanism for incorporation of changes. As the Orbital ATK COTS development activity unfolded, the understanding of requirements between NASA and Orbital ATK evolved and in some cases diverged. The absence of a formal change process was less than optimum and resulted in an informal balancing arrangement that worked well for smaller back-and-forth changes, but was not deemed effective for larger changes. In the end, Orbital ATK and the NASA COTS Program were able to negotiate outstanding issues, but noted the potential advantages of a more formal process to address more significant changes.
Application: Planning for future SAAs should include a mechanism by which changes can be managed effectively.

LESSON: Create a Change Control Process within Future Space Act Agreements-1
Due to the nature of the COTS contracts, there was no remedy for changes that inevitably came down the pike. Systems of bartering and negotiation the true intent can help offset an impact, but partners are working on a fixed budget and NASA will need to be sensitive to any change after an agreement has been reached.
Application: A change control process should be established for future Space Act Agreements.

Evaluation of SAA Applicant Proposals
LESSON: Ensure Partners Are Capable
COTS managers cited the importance of ensuring the prospective partners (selected partners) have the necessary technical, management and financial capability to execute on the FSAA and accomplish milestones.
Application: This speaks to the importance and rigor of the source selection and due diligence process.

LESSON: Establish an Investor Perspective in Evaluating Business Plans-1
Evaluate proposals for public/private partnerships from the perspective of an investor. The perspective should include a trade of partner stumble vs. success. Evaluators can easily get carried away with the potential of a proposed system while not fully appreciating the outcome if a partner stumbles. In case of stumble and termination, is the agency going to own hardware or IP of a failed system? “I took the business education and I found that helpful to learn how to use the investment sheet and understand the business aspect of the proposals.” In discussions about raising capital, it is important to have a good product and a good salesman, such as a good investment banker, who can articulate both the business plan and the technical vision behind it. Venture capitalist investors typically invest in people who can “mom” the whole program/product through to the end.
Application: Future SAA partnership proposal evaluations should incorporate investor training and business education classes to include reading investment sheets and evaluating returns, opportunities and risk from an investor perspective.

LESSON: Establish an Investor Perspective in Evaluating Business Plans -2
Thinking like an investor will help an evaluator of proposals ask the right questions and perform the correct level of due diligence and analysis to ensure agreements are issued to viable partners. Evaluators should ensure that partners have viable business plans outside of NASA. Meet the proposer in person to judge their level of commitment. The COTS Program hired a venture capitalist to assist in evaluating proposals. “He had an interest in space and was full time during the two competitions. He helped us understand how to think of this investment. He helped us think as investor. He helped us think of what to ask for. We added some of his language in our announcement. He helped us analysis the data and proposed that there be a due diligence phase and ask tough questions and build our confidence in the plan.”

Application: During source evaluation boards for any procurement, evaluators can use this lesson to successfully choose the right partner or contractor.

LESSON: Meet with Potential Partners During Evaluation
During the due diligence phase of evaluating proposals, the Participant Evaluation Panel (PEP) found it very effective to go to the vendor facilities and meet the key team members face-to-face. The onsite meetings provided additional insight to the proposals regarding the maturity of the company and resources available to accomplish the proposed plan. Taking tours and sitting across the table from the vendors allowed the PEP to get proposal clarification in person rather than through written statements.

Application: Understanding whom you will be entering an agreement with is vitally important before entering into a partnership. The face-to-face, onsite meetings at the vendor locations provide another data point to determine which vendor(s) are best suited to accomplish the proposed work.

LESSON: Cost, Safety and Reliability Are Key Components of Mission Success
“When the DoD sought out to develop a new launch vehicle, they used Other Transactional Authority (OTA), which is conceptually similar to NASA’s funded Space Act Agreement acquisition method. At that time, [the DoD] was especially concerned with affordability and developing a series of cost-effective launch vehicles.” Many other spaceflight programs have been cancelled due to cost reasons as well, primarily because cost was not included as a motivating factor like safety and reliability. With COTS, NASA leveraged “the private sector’s understanding trading cost and schedule and potentially other factors to come up with a system that is viable in the commercial market place and can [also] meet NASA’s needs and objectives.”

Application: All three objectives -- cost, safety and reliability -- should be written into a program’s objectives. To prevent cost overruns, delayed schedules and cancelled programs, cost effectiveness must be included as a primary program objective.
**Milestone Criteria Development and Definition**

Introduction: Milestone payments mapped to an agreed upon set of objectives allow NASA and the commercial partner to maximize the alignment of incentives to achieve technical progress on time. This payment method optimizes the partner’s cost and schedule because incremental Firm Fixed Price payments are only paid once a milestone is completed. The sooner it’s completed, the sooner the partner gets paid. There is a misnomer that schedule slips result in higher government costs (due to NASA’s common use of FAR-based, cost-plus contracts). But in an incremental FFP payment structure, the fixed payment is tied to the milestone and does not increase if the schedule slips. Incremental milestone payments incentivize vendors to maintain cost and schedule. If the schedule slips, it costs the industry partner -- not the government -- more to get back on track.

**LESSON: Ensure Careful Structuring of Milestones**

Upfront and early-on planning and coordination with legal, procurement, program and other stakeholders is critical. Planning is also critical in the development and negotiation of milestone criteria. “Planning is key. Incorporate corporate knowledge, formulate the team -- developing milestones -- and allow companies to be flexible and innovative, but taking into account lessons learned. Structuring the milestones is really key. The Space Act Agreement is the document the companies and NASA are agreeing to.”

*Application: In future FSAAs it is important to recognize that FSAAs require rigorous and concise definition of “the what” (milestone entrance criteria) while at the same time allowing great flexibility in defining how compliance with the criteria is accomplished.*

**LESSON: Create a Balance in Developing Milestones**

There is a balance that should be struck when developing performance-based financial milestones. They should not be overly prescriptive to dictate how a contractor should operate outside of their best practices. Ideally, the milestones should be defined at a high enough level that they can be effective to allow for efficiencies and still have enough structure for NASA to manage the company and program performance.

*Application: This level of definition to a milestone can be applied for entrance criteria for design reviews. Commercial partners will have their own set of internal entrance criteria that will have to be met. Prescribing all the NASA requirements may prohibit efficiencies in a commercial program.*

**LESSON: Establish Both Technical and Financial Milestones**

The funded Space Act Agreements were structured with both financial and technical milestones with progress payments linked to specific milestones. The process served to incentivize partner cost control, schedule performance, and the attainment of financial and technical goals. Milestones included traditional key decision point reviews such as Critical Design Review. Several interviewees noted the importance of also establishing milestones that require functional demonstration and/or test of hardware.

*Application: This simple acquisition management approach was a powerful attribute of the COTS approach and a key success factor. Future capability development activities should seriously consider*
incorporating payment-linked milestones (financial, development, and demonstration/test) in the formal FSAA.

LESSON: Develop Milestone Performance Success Criteria with More Specific Detail
“The devil’s in the detail.” While striving to avoid dictating “how-to” solutions for high-level functional performance requirements it became apparent that both the commercial partner and NASA needed better, more specific definition of success criteria as well as entrance and exit criteria for each milestone.

Application: This lesson is broadly applicable to all future FSAA activities. Upfront and early-on, spend the time necessary to articulate in greater detail what is expected at each milestone.

LESSON: Avoid Complex Oversized Milestones / Break Into Sub-Milestones
While validating the efficacy of the milestone approach NASA learned that huge, complex, design-related milestones (with thousands of pages of documentation) are to be avoided. Learning the lesson in real time, the COTS team developed a sub-milestone approach that proved more manageable for the commercial partner as well as NASA. Another benefit of the sub-milestone approach was that it provided more frequent payments to partners based on accomplishing individual sub-milestones.

Application: The sub-milestone approach is a broadly applicable lesson for future FSAA activities.

LESSON: Tailor Your Approach to Requirements Definition and Project Management Controls
The COTS requirements management process was unique in that very few “how-to” requirements were levied. Instead, performance criteria were defined and attached to specific milestones. “We did not actually have any requirements on COTS. We did provide what would be the future requirements so that they could think about them. For COTS they had to meet the intent of the milestone criteria.” ……

"We used the parts of the culture that made sense and did not use that were burdensome, overbearing or not applicable to the job we were doing.” ……We took the standard basic management processes and tenants and implemented the ones that make sense. We used concepts from NPR 7120 and NPR 7123, we actually developed our entrance and exit criteria for technical milestones right out of 7123. We tailored them a little bit consistent with implementation by a space act agreement partner …”

Milestones included programmatic, design reviews, hardware tests, and financial as well. A key thing the milestones were used for was to negotiate back and forth with the partners when we were going through the acquisition process. We could better understand the weakness of a partner so we could add and change the agreement before it was signed with the partner to mitigate risk during due diligence. We could add and change the milestones as proposed to mitigate risk we saw during due diligence. …” It should be noted that the traditional, more directive NASA requirements and compliance philosophy was fully implemented when it came to rendezvous and docking with the ISS.

Application: The COTS FSAA tailoring approach should be considered for future development activities where equivalent procedures and flexibility can be tolerated while demonstrating compliance with the intent of agency program and project management and systems engineering philosophies.

Lesson: Don’t Overprescribe Requirements
“I have been involved in many programs. Some government agencies tend to be very prescriptive and that results in the people responsible for the synthesis of design and the development of the system becoming sidetracked in feeding the customer and trying to satisfy a lot of customer requirements that may be over prescriptive. That approach tends to drive up the cost of a program and defocuses some of the folks that are key to the program. Excessive reporting - making charts and graphs diverts focus away from the real task at hand which is to synthesis, design, develop and test a flight system."

Application: Issuing a Space Act Agreement should not come with prescriptive requirements. Inserting fewer technical and programmatic requirements doesn’t mean less insight but will certainly mean less cost.

LESSON: Align Incentives with Strategic Goals and Objectives
Milestones were not launch-based because that could have incentivized partners to fly before they were truly ready. Instead, milestones were tied to the methodical development of new capabilities along a streamlined project management lifecycle -- not rushing to end goal before the system passed necessary test and verification criteria. Additionally, when validating a human crew transportation system, more requirements are necessary, resulting in more cost, schedule and technical verification.

Application: In a capability development partnership, the milestones enable a stepping-stone approach to technical and safety standard compliance. Key NASA standards are still verified, but linking them to properly aligned incentives results in a faster, more cost-effective development cycle.

Managing the Funded Space Act Agreement
This section is organized using the following structure:
- Staffing
- Communication
- Tactical Management of Milestones

Staffing
LESSON: Establish a Small Team of Experienced Managers
The COTS Program Office was staffed with 10 full-time employees who managed the FSAAs with partner organizations. The experience and philosophical orientation of the team was important to the program success. Specifically, the COTS organization had the experience necessary to manage requirements implementation in an open-minded fashion -- critically evaluating why a particular requirement exists, applicability of the requirement, and equivalent ways of demonstrating compliance. “…The staff has to possess the experience to understand the basis (intent) of the rules …” “… Our group understood the underlying philosophies and had the flexibility, ability and open mindedness to make it work.”

Application: Innovative partnership management teams need to be staffed with experienced personnel who are capable of envisioning and supporting new ways of doing requirements. The wrong composition of an FSAA management team will limit the project potential.

LESSON: Consider Intergovernmental Personnel Assignments to Develop Capability
Several individuals from NASA’s Ames Research Center worked at SpaceX under Intergovernmental Personnel Assignments (IPAs), specifically supporting development of the Dragon PICA heat shield. In addition to transferring technical expertise, these assignments provided orientation and insight into the commercial culture and development paradigm contributing to the COTS FSAA success. 

Application: IPAs should be considered as an element in the grooming process for potential managers and key personnel on FSAA management teams.

**Lesson: Develop and Leverage One’s Own Professional Network**

Broadening one’s professional network and establishing agency-wide relationships is essential for tapping into the right resources and forming a team when the necessity arises. One Wallops stakeholder stated, “I had a group under me called Rocket Propulsion Test, which were all the test cells across the agency. That was educational for me and I got to know a lot of people and the capability at the centers.” Subsequently, this individual was able to draw on subject matter experts from KSC for launch pad construction, SSC and WSTF for rocket testing, and MSFC for liquid propulsion expertise. Having developed these relationships across the centers over a career, the individual helped to enable a swift knowledge transfer to the commercial partner and construction manager to draw on decades of experience. The knowledge sharing occurred because the WFF lead had developed these relationships and knew who to call for solutions to specific issues.

*Application: Get to the centers and see what the agency has to offer. Don’t get buried in one specific work area, but rather, take in the capabilities that exist within the agency and grow your network.*

**Communication**

**LESSON: Communicate to Develop Trust**

Open communication, trust, transparency and a positive, badge-less team environment were identified as critical success factors. “…Everyone needs to act as one big team to make the Space Act Agreement arrangement successful” … “Everyone needs to adhere to the same goal. We built trust.” “Early on engagement and communication are key” … “Transparency is important” … “There was no hierarchy.”

*Application: Future innovative FSAA partnerships should ensure leaders embrace “soft skills” necessary to nurture open communication and a collaborative environment.*

**LESSON: Communicate to Clarify Roles and Define Accountability**

In an FSAA (space system) NASA, the commercial partner and other regulatory stakeholders (e.g., FAA, DoD, NTSB, EPA) and local authorities have varying degrees of authority, jurisdiction and accountability for public safety and mishap response. “… Managing expectations is important. For the demonstration mission to ISS, we spent a lot of time managing expectations. These were FAA-licensed launches, so the companies were responsible. For the first demonstration mission we were reminding the NASA Technical Authorities that this is not a NASA mission and that while we will have a member on their mishap team we are not running it.”

*Application: FSAAAs, while an exciting and innovative acquisition method, may become complicated when it comes to adverse outcomes, especially a launch, re-entry or on-orbit mishap. Adequate planning,
coordination and communication are essential. HEOMD, in fact, conducted a mishap simulation prior to the first COTS launch to ensure stakeholders were all on the same page in the event of a failure.

LESSON: Mentor vs. Overseer
The funded SAAs brought a completely new way of conducting business to NASA. One contributor added the following anecdote regarding the COTS model of “insight” rather than “oversight.” “I have worked these types of partnerships before. I think a lot of people struggled with the concepts of partnership versus the government contract where requirements are laid down and compliance is expected. In a partnership, you get to be more of mentor and coach rather than in an oversight role. This structure [allowed for a considerable] amount of design changes happening at a faster pace than a lot of people were used to. In an SAA construct, the partners are motivated to constantly improve their design. In a cost-plus contract, with traditional Government oversight, changes occur [more] slowly. It is difficult to make changes and those changes can be very costly.”

Application: The SAA-based public-private partnership promotes innovation and rapid design iterations. This agreement structure can be significantly less costly than a cost-plus contract when applied to a reasonably mature technology or system project that industry is capable of developing and selling to other customers.

LESSON: Conduct a Kickoff Meeting
When the COTS program started the commercial partner teams went to JSC, separately, to have a multi-day face-to-face meeting. It greatly helped to build relationships since people could interact with each other in close proximity, not just hearing each other’s voices over the phone. Each subsystem spoke with its counterparts to get an understanding of top-level philosophies, approaches, etc. This type of meeting also facilitated a “duplex loop,” where all parties engage in a back-and-forth conversation that increased understanding on all sides. The relationships built there were maintained with weekly top-level teleconferences, furthering frank and free exchanges. The government partner also observed at FRBs and MRBs. They were invited to all by the commercial partners.

Application: When starting a new partnership where relationships will make or break the endeavor, start the program with a broad kickoff meeting, preferably at a NASA facility. This frank and free exchange should be followed up by weekly meetings, and the government partner should attend, (even if only as an observer) important decision reviews and technical interchange meetings.

LESSON: Trust but Verify – Selectively Request Independent Analysis
The funded Space Act Agreement structure with commercial partners was very different from typical Federal Acquisition Regulation (FAR) procurements. The SAA had no hard requirements, rather only goals and objectives to complete a series of demonstration missions in low Earth orbit. This structure promoted innovation within the commercial partners, but altered NASA’s standard, rigorous verification process. The COTS leadership decided to focus its limited verification resources on the historically most critical and riskiest aspects of mission. One contributor shared, “We did quite a bit of independent analysis. I deployed a bunch of resources to watch the demo missions from an independent NASA data collection perspective so that we could validate what SpaceX was telling us with our own data. If
something had gone wrong then I would have had independent data to piece things together for the failure investigation. [Additionally], I had the debris radar (that shuttle had developed) turned on for the first couple of demonstration flights. We [also] deployed the Shuttle recovery ships and used their x-band radars to see the critical staging events where failures typically occur.”

Application: These are good examples of how to effectively conduct due diligence in the right areas, especially when trying to back off on oversight. Leveraging NASA’s world-class monitoring methodologies and various disciplines is an efficient way of conducting targeted independent assessments of commercial partners’ performance.

LESSON: Negotiating Requirements - Maintaining “Healthy Tension”
The NASA COTS management team worked with ISS subsystem managers along with SMA and engineering Technical Authorities to define -- through a negotiating process -- the essential, minimum set of functional requirements for vehicles operating within proximity of the ISS. These requirements were articulated in SSP 50808. The COTS team then worked with commercial partners to tailor those requirements (if relevant to the specific vehicle/mission) and negotiate compliance verification (demonstration) methods. Throughout this process there existed a “healthy tension” between all stakeholders.

Application: The COTS implementation example is a model for future capability development and commercial space activities.

LESSON: Let Schedule Slip (If Moving Forward) – It’s a Different Ball Game
NASA project managers typically grind their teeth when faced with schedule slips that invariably translate to large cost overruns. The FSAA approach is a game changer. Schedule slip is decoupled from cost overruns. Lack of progress results in lack of payment. “...If progress is still being demonstrated then who cares what the schedule is. We knew the schedules were very aggressive. We knew from day one that the schedules were not realistic. We did not worry about not meeting milestones on a super aggressive schedule....”

Application: Most NASA development efforts are cost plus fixed fee contracts with no incentive to hold down cost. FSAAAs with milestone payments shift the risk to the contractor. The advantages of FSAAAs, as appropriate, should be considered during acquisition strategy meetings early in program/project formulation.

Tactical Management of Milestones
LESSON: Specify the What -- Not the How -- and Allow Flexible Demonstration of Compliance
A fundamental and arguably super-critical knowledge point for the COTS FSAA project management design was the decision to omit detailed how-to Safety and Mission Assurance requirements and standard FAR procurement oversight provisions. The participants decided (their option) to also seek to demonstrate compliance with the traditionally proscriptive ISS rendezvous and docking requirements contained in ISS SP 50808. In this case partners were allowed flexibility (with NASA approval) in the method for demonstrating compliance with critical safety requirements.
Application: Project planners for future FSAA projects should consider the COTS model as a basis for defining, implementing and managing requirements, enabling flexibility and innovation as the ultimate goal of the FSAA.

LESSON: Recognize and Accept Partners’ Procedures When Equivalent
For the most part the commercial partner had the same process or procedure that met the same criteria or objectives of ones that were created at JSC. The commercial partner would tailor the procedure for the program from a corporate standard. The tailored version would then be shown and explained to the counterparts at JSC, followed by striking an agreement to use the tailored process on COTS. This was successful on a number of instances, such as fracture control.

Application: If the commercial partner already has processes or procedures that meet the objectives and intent of a needed NASA process or procedure, then the commercial partner’s process should be tailored for the project and explained to the pertinent NASA team, and an agreement should be reached to use it.

LESSON: Maintain a Lean Insight Approach
Having a relatively small group of individuals with insight into a program allows the commercial partner to remain focused on the core tasks at hand. It also allows for cleaner and crisper lines of reporting and direction on both sides as well as streamlined communications when issues occur.

Application: This philosophy can be applied to both Space Act Agreements as well as traditional government programs. Traditional government programs will have to learn not to overload the contractor with large boarding parties and too many customer points of contact with their own agendas.

LESSON: Employ Milestones as a Risk Management Tool
Milestone payments have two effective risk mitigation attributes.

(1) NASA has the ability to tie milestone payments to perceived areas of partner weakness. In the case of Rocketplane Kistler (RpK), the company’s private fundraising was an area of concern. Early milestones were financially focused and emphasized set amounts of private fundraising in order to achieve the milestone and move on to the next gate. When RpK failed to accomplish the milestone or show substantial progress toward meeting it, NASA terminated the agreement with no additional liability.

(2) Milestone payments also force industry partners to put “skin in the game.” Under these agreements, the government’s contribution to the project is fixed and will not grow due to project overruns. This payment structure limits NASA’s exposure to any unforeseen project cost or schedule growth. The industry partners take on any additional costs themselves, which acts as a forcing function for them to operate as efficiently and quickly as possible. The quicker they accomplish a milestone and the less it costs them, the more return on investment they receive from the milestone payment. Conversely, other contract structures can result in unintended incentives of continuous cost and schedule growth as the vendor makes more money the longer the project stretches out.
Application: While NASA does not manage requirements in a public-private partnership, milestone payments instead act as the government’s risk mitigation tool through mitigating partner weaknesses and forcing companies to put “skin in the game.”

Lesson: Plan Realistic Achievable Goals for Each Milestone Review
Success criteria for milestone payments should be carefully crafted with the end in mind. Additionally, the same level of effort should be paid to milestones leading up to the event or gate criteria. Milestones need to be clearly documented to outline agreed upon success criteria. You should talk early and often to document any expectations and underlying requirements for success. Be flexible if progress is being demonstrated. “If you start talking about the milestones well in advance, I would say there were very few instances where they would fall short. We pre-negotiated if it looked like a milestone was not going to be met.”

Application: This can be applied to any Firm Fixed Price Contract, Space Act Agreement or Purchase Order with fixed milestones.

LESSON: Write Explicit Milestone Language and Explain Success Criteria
The initial COTS milestones were high level and open to interpretation from the commercial partners’ perspective. As the COTS program progressed and milestones were altered or added, NASA improved descriptions of the deliverables necessary to achieve the milestones. Additionally, the NASA Program Executive assigned to Orbital ATK generated WBS criteria to detail expectations for each milestone prior to commencing work on that milestone. This three-to-four-page document produced actionable tasks at the right level for management and production to work toward. While this was not a “requirements document,” it was written and intended to provide milestone clarity and reduce uncertainty and miscommunication.

Application to Exploration: When implementing the milestone payment structure, it is essential to further refine the goals and objectives into discrete work packages.

LESSON: Measure Progress by Testing, Not with Paper Reviews
One contributor shared, “If you really want to innovate you have to get out of the mainstream of the company. In a big company, there are many processes and requirements, and they are passed on to every new project. If you split off from all the overhead requirements, then you can be less burdened with paperwork. The flexibility allows you to implement those processes that are inherently efficient or value added. We were flexible about paperwork and didn’t worry about format as much as the [underlying] technical content. We tried to look at it from a big picture systems level. We tried to make sure the intent was there to meet the system level requirements to make sure [we understood] the integrated system works.”

Application: Large organizations create and pass down requirements based on prior events. Many times the intent of the requirement can be lost, leaving multitudes of prescriptive requirements and review processes – not that those are not important. But many times they can be streamlined to help project implementers focus more on the “what” and less on the “how.”
LESSON: Establish Clear Milestones and Success Criteria
Milestones that are concise (less than one page) and understandable by all (not just the author), with clear expectations of output, are important for measuring progress, understanding the state of the commercial partner, and maintaining partner relationships. Be ready to make changes to agreements numerous times, based on new understanding. A milestone for one commercial partner’s launch vehicle stage assembly completion ended up being dependent on the completion of a connected stage.

Similarly, another partner and NASA had different expectations for what it meant to complete a launch vehicle stage assembly milestone. Discuss the milestone’s intent, criteria and “requirements decomposition” with the partner months ahead of the scheduled completion date. Established line-by-line understanding and expectations are crucial for smooth and successful milestone completion.

Application: Milestones and associated criteria need to be concise and broadly understandable. As the milestone approaches, discuss the details and expectations of the milestone criteria with the partner. Be flexible and prepared to change or add milestones as the program progresses and better understanding or resolution is gained.

LESSON: Maintain a Steady Cadence of Progress through Milestones
"We told the companies - tell us what the capability is that you are developing, how far along you are and provide us with milestones that fit your development timeline. We did not specify that you must have this milestone and that milestone [but] we told them they had to have at least one milestone per quarter. At a minimum, [we requested that partners] must have a milestone for a demonstration flight."

Application: The progress milestones were used as a measure of progress and risk mitigation tool for NASA. Having a steady schedule of properly spaced milestones allows the government to measure progress and make decisions on whether the partner has demonstrated sufficient progress to continue in the agreement. Additionally, having too many milestones too often can put an increased burden on partners to spend more time on reporting.

LESSON: Milestone Schedule Slips
Fixed price SAAs with payment based on accomplishing milestones ensure the government cost liability is limited. “We found our partners had the typical delay of any new launch systems. There was an understanding that schedules are a bit optimistic. In this case, the government costs did not go up because of schedule delays. The costs of delays were coming out of their pockets.”

Application: When determining contract type and milestone schedules for any procurement, ensure that milestones reflect a realistic schedule and can accurately reflect partner performance.

LESSON: Streamlining Milestone Payments
The COTS team worked with the NASA Shared Services Center (at Stennis Space Center) to streamline the process of issuing payment to commercial partners. Cash flow margins are typically thin in the commercial start-up/entrepreneurial environment. Cutting payment times from multiple weeks to multiple days was a COTS-enabling process innovation on NASA’s part.

Application: The streamlined payment process is a best practice applicable to all future commercial partnership projects.
LESSON: Ensure Rapid Invoice Payment

Understanding a partner’s motivation will help enable a solid business relationship. In the case of publicly traded companies, there are financial goals that have to be met, which in turn may affect the stock price. Be mindful of quarterly and year-end closeouts and how they play into a milestone payment plan. Flexibility and understanding may pay off in the long run. “NASA was able to pay us quickly and get payments on the books in a timely fashion. The more NASA can understand how to work with a publicly traded company the better. Partners are subject to a broad range of financial requirements including public reporting requirements, year-end close, Wall Street reporting, quarterly cycles, shareholder and investor reporting. It is hard to get payments to line up sometimes. NASA tried to be as sensitive as they could to a commercially traded company like ours. The flexibility NASA exhibited was admirable as they tried to be as sensitive as they could to the needs of a publically traded company like ours.”

Application: Any time NASA does business with a publicly traded company, management teams should be cognizant of the company's motivation to reach certain milestones and the importance of receiving the associated revenue.

LESSON: Share Data Well in Advance of Milestone Reviews

The milestone data packages were provided 60 days ahead of the respective event. This allowed plenty of time for NASA to review, draft actions, etc. The milestone event was then more of an overview with a focus on future plans.

Application: Submit milestone data packages and material well ahead (60 days) of the event to enable thought-out feedback and time to resolve any concerns that might exist. This also allows the milestone to focus on future efforts.

Supporting Commercial Partners

This section is organized using the following structure:

- CAT Concept
- People
- Technical Support Examples

CAT Concept

Lesson: Establish an Assistance Team Budget

For the COTS effort there were between four and five FTEs allocated for the COTS Advisory Team (CAT). The intent was to put as much of the money with the partners and have as lean a team as possible on the government side for administration. More funds should have been set aside for a more robust CAT and related effort. For Commercial Crew there were approximately 13 FTEs allocated for the advisory team.

Application: Have sufficient funding for the advisory team. For a program the size of COTS or Commercial Crew, allocate five to 15 advisory team members.
LESSON: Recognize and Leverage the Agency Knowledge Base
The largest contribution NASA could make in this endeavor was a financial investment (initially $500 million), but a close second is the corporate knowledge transfer of 50 years of NASA know-how to the commercial partners.
  - The CAT was established as a group of agency-wide technical discipline experts who were on call and willing to provide technical assistance.
  - All test and verification requirements were done with these NASA subject matter experts. The CAT members only supported their role on a part-time, as-needed basis, which caused minimal impact to their primary job functions.
  - It was endorsed by the center directors and received top-down support.

*Application: NASA has a world-class breadth of engineering and aerospace knowledge within its technical workforce. Managers should recognize the technical expertise available across the agency and make an effort to leverage discipline experts across the centers and support facilities.*

LESSON: Tap into NASA’s Corporate Knowledge
The NASA Program Executive for SpaceX implemented a matrixed team of subject matter experts across the agency. He contributed, “I was one of the managers at Constellation for test and verification and had to set up a matrixed support organization from all different centers. I used this experience to help set up this type of scenario we had in COTS. In this project, I needed some [people] from Johnson Space Center who had experience with spacecraft; I needed people from Marshall Space Flight Center who had propulsion experience – an understanding space shuttle main engine development, Apollo, rocket design. We pulled on people to help run baseline thermal analysis on the rocket. We even tapped some [experts] who worked on Apollo.”

*Application: When setting up a new program, think broadly about which NASA centers have applicable resident expertise and engage subject matter experts from across the agency.*

**Lesson: Transfer Operational Experience**
NASA had a lot more experience than the commercial partners regarding the complex mission operations that are needed to perform a rendezvous between two spacecraft. These experiences were gained from space shuttle, HTV, ATV, Soyuz and other operations. These best practices, including flight rules, were then transferred to the commercial partners and rehearsed thoroughly. This allowed for predictable yet flexible responses to contingencies while ensuring the ISS and the crew onboard was safe.

*Application: Determine in what aspect of the mission the government partner has far more experience than the commercial partner and ensure that the commercial partner is thoroughly educated based on that experience.*

**People**
**LESSON: Find the Experts**
The COTS management team emphasized the need to find individuals who “know the reasons” behind a given requirement, not just that the requirement exists. CAT members were invaluable when they could relate individual safety or engineering requirements to specific engineering principles, mathematics,
past failures and operational experience. CAT members assisted partners in assessing and developing design margins, factors of safety, and/or approaches for exposing latent defects in a design, process or operation.

Application: Future FSAA managers should seek out individuals with senior technical expertise, knowledge and experience from center SMA and engineering organizations to serve on partner support teams.

Lesson: Incentivize CAT Participation
The CAT member’s role was to be an expert consultant who could pass on their view and lessons learned, while the final decisions were up to the participating companies. Typically, the members focus on a project for many years or a large portion of their career. Members were offered a chance to work on several projects that could be accomplished in a relatively short period of time, which made it easy to attract members and convince them this was a fun and stimulating approach.

Application: Advisory team members need to understand that their role is that of an expert consultant. To attract talent, offer them the opportunity to simultaneously work on multiple projects in a fast-paced environment.

LESSON: Develop a Team of Volunteers
The COTS team developed and coordinated an extensive contractor support effort called the COTS Assistance Team (CAT) that provided support to commercial partners. The CAT approach enabled the COTS program office to remain small with a backup from 100 technical experts who were funded to a great extent by other major programs. “We helped them mature their technology from a technical perspective. We had lessons learned. We had experts. We could provide them technical expertise to allow them to continue to mature and develop their systems. We provided some fantastic guidance, history, and analysis to allow them to better develop their systems. We sent an open letter to all Centers and said we are looking for technical experts in specific areas. We built a roster of 100 NASA folks in various disciplines—such as TPS, avionics, propulsion and other major disciplines. They functioned as our technical experts evaluating and assessing our partner systems. When we got to the point of trying to close milestones we had the technical folks around NASA reviewing engine test results, CDR packages, and avionics test results. Our experts also provided questions and comments to our partners in preparation for major milestone reviews. …”

Application: The CAT support activity is a good technical support model for future FSAA development activities while recognizing that internal charge accounting has the potential to emerge as an issue.

LESSON: Integrate Mentoring into the Technical Assistance Model
The COTS Advisory Team reached across the agency to pull subject matter experts from many disciplines. While implementing technical knowledge transfer, the COTS team discovered the power of mentoring. One contributor added, “It is partially a mentoring program - bringing new engineers to work side by side with the older engineers drawing on their experience. It is hard to write down some of the stuff embedded in one’s experience. The commercial partner could get the specific knowledge [it needed], and it seems like a mentoring program is the way to go to. [Additionally], you want your
engineering staff to work on multiple programs through their career because they go through many failures and learn what works and doesn’t work and they can share it with the newer engineer. Part of learning is making mistakes.”

*Application: Instituting a structured mentoring program within an organization can be the most efficient way to transfer knowledge amongst personnel. Encouraging periodic work rotations can enhance the effects of mentoring by acquiring knowledge in different facets of a discipline.*

**Technical Support Examples**

**Example: Safety Review Panel and System Safety Review Process**
The Safety Review Panel (SRP) process was unfamiliar to the commercial partners. They were also unfamiliar with cargo processing operations, but hiring subcontractors and experts who have experience in ISS cargo loading processes helped a lot. The SRP process can easily be underestimated for its ability to create a parallel set of requirements mid-development. Simple things, like the definition of an "inhibit," can easily cause consternation due to a “cultural impedance mismatch.” Once the partners at the project and corporate level got acclimated to the nature of the SRP, the subsequent phases were better. It helped that the COTS Program management team also communicated with the SRP to help its members understand the impact of their decisions on the commercial partners.

*Application: Anticipate the SRP process having a significant impact on safety-related aspects of the design. Do not assume that one person or group’s interpretations are the same as the SRP’s. Have an onsite NASA SRP expert who can provide “black belt” advice on the SRP process as a whole, expectations of the SRP members, etc. They have “high bandwidth to the mother ship” and can be instrumental in smoothing out any points of friction between organizations.*

**Example: NASA-approved Use of Automotive Grade COTS Components**
An important takeaway from the program was the use of commercial-off-the-shelf electronic parts rather than using the more expensive S-level parts. One interviewee stated, “Early in my career I did a lot of phase A and phase B studies, and used some [industry standard] price models. No matter how I tweaked the model and complexity factors, I noticed a trend that the electronics and avionics in the system software seemed to be the primary cost and schedule driver of the overall project. If you can use more commercial electronics and learn to build things faster in the electronics area, it reduces the overall product schedule and drives the overall cost down dramatically. Thus, it becomes cheap enough to build a lot of redundancy into the system resulting in more reliability. The commitment of the organization to do things faster and better was a big thing we learned from SpaceX.”

*Application: Avionics software and electronics are historical cost and schedule drivers. Innovative solutions such as utilizing automotive grade electronics can dramatically reduce cost without negatively affecting the system reliability.*

**Example: Cygnus/ISS Interfaces: Hardware, RF, Software**
JSC ISS Program technical organizations provided extensive support to Orbital ATK in addressing interface definition and compliance testing for three key areas: (1) mechanical (berthing mechanism),
(2) RF (talking directly with ISS through telemetry), and (3) software, including interfaces, safety, and fault tolerance.

**Example: Cygnus Micrometeoroids and Orbital Debris (MMOD) Shielding Design**
JSC experts supported development of MMOD shielding on Cygnus vehicle, specifically related to penetration modeling of various material “stack-ups” and subsequent ballistics testing conducted at White Sands Test facility (WSTF).

**Example: SpaceX PICA Development**
NASA Ames Research Center supported SpaceX in development of the Dragon reentry thermal protection system (TPS) -- phenolic impregnated carbon ablative (PICA). Over a nine-month period, SpaceX developed the in-house manufacturing capability for PICA at their Hawthorne facility.

**Example: SpaceX CUCU Development**
NASA assisted SpaceX in developing the COTS UHF Communication Unit (CUCU), which provides a bi-directional, half-duplex communications link between Dragon and ISS using existing ISS UHF Space-to-Space Station Radio (SSSR) antennas. The CUCU was tested on STS-129, passing a series of tests verifying the capability to allow ISS crew members to monitor and command approaching or departing Dragon spacecraft during cargo delivery missions.

**Example: SpaceX DragonEye LIDAR**
NASA assisted SpaceX in developing and qualifying its DragonEye Laser Imaging Detection and Ranging (LIDAR) sensor with demonstration testing on Space Shuttle Endeavour, STS-127. The DragonEye LIDAR system provides range and bearing information from the Dragon spacecraft to the ISS.

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**Operating in the ISS Environment**
This section is organized using the following structure:
- Requirements & Flight Rules
- Simulation / Demonstration / Rehearsal

**Requirements and Flight Rules**
**LESSON: Consider Establishing a “Single Book” for NASA Requirements**
The ISS developed a single consolidated document containing safety and operational requirements for proximity operations with ISS. Several individuals noted the importance and advantages of collating NASA requirements into a single document rather than flowing down a library of requirements contained in NASA policy and procedural documents. It was noted that each NASA policy and procedural document typically invoke a list of additional “applicable documents,” that in turn refer to others. The ISS Program team endeavored to create a single document SSP 50808 that was largely self-contained
with a minimum of references. Further, SSP 50808 combined or flattened requirements typically contained in a hierarchy of descending documents reflecting mission directorate, program, and project management levels (Level-1, Level-2, Level-3).

**Application:** The “Single Book” approach is a key concept to incorporate in future SAA projects because it will provide a user-friendly way for NASA to flow down the proscriptive requirements necessary for human spaceflight and other activities where risk tolerance is low.

**LESSON: Ensure Implementation of a Robust Safety Review Process**

Hazard analysis and hazard control are central concepts employed by NASA in evaluating the readiness of a vehicle to approach the ISS. The SRP is a methodical three-phase process designed to identify safety hazards and risks, and then alter design and/or implement mitigation measures or operational controls for each hazard. The SRP Phase 1 includes hazard identification and conceptual control approaches. Phase 2 is a refinement, and Phase 3 involves verifying that control concepts are actually implemented in the design.

**Application:** Implementation of a safety review process based on mature system safety engineering concepts should be a necessary element in the design of all mission-critical space systems.

**LESSON: Revisit the “Why” – Negotiate and Tailor**

Re-examine the rationale behind every requirement. Requirements drive cost and schedule. Overly prescriptive requirements (how-to) inhibit innovation. The COTS project, ISS subsystem managers, commercial partners, and agency Technical Authorities engaged in a “fresh set of eyes” dialogue that drove to identify the fundamental and functional intent of each proposed requirement. They also sought to identify the assumptions associated with each requirement, which in some cases may no longer be applicable. The ISS support team, drawing from both HTV and ATV rendezvous and docking experience, articulated the rationale behind the really (as quoted) important requirements. The process was hugely enabled by the participation of SMA experts that brought the necessary knowledge and experience to explain the intent, rationale and failure experience driving individual SMA requirements. The negotiation process also extended to requirement verification wherein commercial partners were provided great latitude in defining the method -- the “how” they would employ to demonstrate compliance with a given requirement. Great care was taken to ensure that specific wording in any requirement would not limit the verification method solution space.

**Application:** This approach or SAA paradigm is potentially adaptable in any future SAA project. NASA defines the “what” or functional need while leaving the “how” to the commercial partner. In fact, this simple concept is fundamental to the entire concept of spurring innovation and development of new capabilities.

**Lesson: Thrash Out the Details Face-to-Face**

For flight operations, the commercial partners were not necessarily of the mindset of being responsible for multiple spacecraft. Even though one was under their direct control. This necessitates dealing with multiple control centers and entities, including the ISS. Flight rules enable the operations to adapt to changing environments in a predictable manner and also facilitate changing flight directors smoothly.
The benefit of having flight rules was not apparent at first. The JSC team met with each commercial partner for a week-long meeting in Houston approximately one year before the scheduled demonstration flight to discuss (“thrash out”) the details and to also illumine the partners on the need for quality flight rules. This meeting was extremely helpful in inverting the partners’ viewpoint on flight rules. The flight rules stood the test of time, minimized issues, and enabled easy transitions between flight operations members.

Application: Have a flight rules kickoff meeting at a government partner’s facility at least one year before the first scheduled flight or launch. It will enable appreciation of the value of flight rules and an understanding of the (initial) rules themselves.

LESSON: Maintain Stable Interface Requirements
“A stable IRD [Interface Requirements Document] is an asset, not a liability.” Changes to the requirements and, therefore, the interfaces should be discouraged. Knowing what the interfaces are from the beginning is far more attractive to an investor. A close working relationship with the ISS Cargo Planning and Integration Office was important for transitioning from an SAA to a service procurement/production. Have your partners back during discussions with others in the agency (such as the ISS) and have the agency back during discussions with the partner. Then hold the partner to the same standard. Similarly, ensure that the Safety Review Panel (SRP), which can drive a parallel set of requirements into the system design, has the partner’s perspective and an understanding of what they are doing to the partner.

Application: The more stable the requirements set, the smoother the acquisition will be.

Simulation / Rehearsal / Demonstration
LESSON: Continuously Verify Control and Capability during Demonstration Flights
NASA developed a step-wise sequence of gates or stopping points to verify the controllability and communication capability of vehicles approaching the ISS. At each gate, checkout activities address rendezvous and proximity operations subsystems, approach software, and vehicle operational health (power, GNC, communications). The process enabled incrementally buying down risk each step along the way to eventual dock.

Application: The step-wise gate approach is a best practice, risk mitigation strategy for rendezvous and docking of space vehicles.

Lesson: Conduct Joint Rehearsals
Joint rehearsals were instrumental for successful demonstration missions --especially, practicing rendezvous was imperative to ironing out the subtle details that occurred, including the interactions between the high fidelity simulators (flight-qualified hardware). “There is a lot of detail and subtlety in the actual commanding of the space craft that the top level observers doesn’t see or recognize. The coordination at the beginning of the program rehearsals was a little rougher than it should have been. The rehearsals allowed us to iron out the rough edges to extent where the coordination worked really well.” After some practice, data sets were flowing smoothly to the Houston team and responses were
provided in a timely manner that fit the very tight mission timelines without disturbing the crew schedules.

*Application: Have bilateral and trilateral joint rehearsals with flight-like hardware simulators.*

**LESSON: Ensure 100% Fidelity in Simulation Activities**

An inflight anomaly occurred because assumptions were made about the side of a communications interface that the commercial partner did not control or design. All other interfaces were simulated in collaboration with other partners that provided EDU or methods of exchanging data in real time. Even vendors of critical path components provided simulators that simulated interfaces for testing.

*Application: Have a strong preference for each interface to be simulated by the organization that operates or manufactures it. Assumptions about the characteristics of interfacing hardware and software represent serious potential failure modes.*

**Lesson: Practice, Practice, Practice**

For the demonstration mission, the Cygnus (Orbital ATK visiting vehicle) was largely finished ahead of Antares (launch vehicle) and the Wallops Flight Facility pad. This provided an opportunity to conduct more and extended internal (to Orbital), bilateral and trilateral rehearsals (JMSTs). “Those JMSTs were incredibly valuable in terms of preparing all parties in the mission for the mission. It got everybody well-versed in how to communicate.” The teams were exposed to multiple anomalies in these simulations, which got everyone well prepared for the day when the mission did not go perfectly well.

Contingency planning was important. There are three meta-level (key) contingencies that the Cygnus team was prepared for leading up to the demonstration mission: aborts, racetrack and software patching. An abort is required if any number of anomalies occurs during close approach to the ISS, making it a great, enveloping scenario. Racetrack is a parking orbit in the vicinity of the ISS that allows a visiting vehicle to get back to the station and attempt the approach all over again. Software patching allows for modification of the flight code while the spacecraft is in flight. Patching rehearsals almost did not occur because we felt that we had done such a thorough job for testing software. We went ahead with the rehearsals and during the Cygnus demonstration mission all three contingency operations, for which all teams were well prepared, were employed -- ultimately resulting in a successful COTS mission.

*Application: Preparation for mission operations is critically important because first missions, especially ones with complex operations, will not occur in nominal manner. It is important to conduct rehearsals both within teams and between teams that will be interacting during flight operations. These rehearsals and simulations should be of the highest fidelity available and the operations teams should be faced with off-nominal situations, including multiple anomalies across multiple systems. Contingency planning and procedures, especially with procedures that are umbrella responses to different types of anomalies, will enable the team to respond in a calm and prepared manner if the mission does not go as planned.*
Appendix A: Interviews

**Interviews**: Interviews were conducted between April 2015 and March 2016 with individuals involved in the management, planning, implementation and operation of the COTS Program.

**Audio Interviews**
- NASA/Andrea Riley/30-Apr
- NASA/Marc Timm/30-Apr
- NASA/Lee Pagel/6-May
- NASA/Valin Thorn/20-May
- NASA/Phil McAlister/21-May
- NASA/Dennis Stone/21-May
- NASA/Alan Lindenmoyer/2-June
- NASA/Bruce Manners/2-June
- NASA/Kevin Meehan/3-June
- NASA/Warren Ruemmele/15-June
- NASA/Mike Horkachuck/19-June
- NASA/Amy Xenefos/24-June
- NASA/Bill Wrobel/25-June
- NASA/Kathy Lueders/8-July

**Audio/Video Interviews**
- NASA/Bill Gerstenmaier/4-Aug 6 Aug
- NASA/Bruce Manners/9-Sept
- NASA/Kathy Lueders/23-Sept
- NASA/Marc Timm/13-Oct
- NASA/Alan Lindenmoyer/7-Oct
- NASA/Dan Rasky/1-Dec
- NASA/Phil McAlister/12Jan
- FAA/George Nield/21-Aug