NASA/TM—2008-215045

AIAA–2007–6196

A Successful Infusion Process for Enabling Lunar Exploration Technologies

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January 2008

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Prepared for the
Space 2007
sponsored by the American Institute of Aeronautics and Astronautics
Long Beach, California, September 18–20, 2007

National Aeronautics and
Space Administration

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Cleveland, Ohio 44135

January 2008

Acknowledgments

The authors would like to thank the Exploration Technology and Development and Constellation Program Offices for their continued support in funding the work to enable NASA's Vision for Space Exploration, the Lunar Architecture Team for their vision of lunar sorties and outposts, and the Lunar Lander Project Office for their cooperative spirit to establish the technology portfolio to meet the lander needs.

Level of Review: This material has been technically reviewed by technical management.

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A Successful Infusion Process for Enabling Lunar Exploration Technologies

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Abstract

The NASA Vision for Space Exploration begins with a more reliable flight capability to the International Space Station and ends with sending humans to Mars. An important "stepping stone" on the path to Mars encompasses human missions to the Moon. There is little doubt throughout the stakeholder community that new technologies will be required to enable this Vision. However, there are many factors that influence the ability to successfully infuse any technology including the technical risk, requirement and development schedule maturity, and, funds available. This paper focuses on effective infusion processes that have been used recently for the technologies in development for the lunar exploration flight program, Constellation. Recent successes with Constellation customers are highlighted for the Exploration Technology Development Program (ETDP) Projects managed by NASA Glenn Research Center (GRC). Following an overview of the technical context of both the flight program and the technology capability mapping, the process is described for how to effectively build an integrated technology infusion plan. The process starts with a sound risk development plan and is completed with an integrated project plan, including content, schedule and cost. In reality, the available resources for this development are going to change over time, necessitating some level of iteration in the planning. However, the driving process is based on the initial risk assessment, which changes only when the overall architecture changes, enabling some level of stability in the process.

Nomenclature

CaLV	Cargo Launch Vehicle
CEV	Orion Crew Exploration Vehicle
CFM	Cryogenic Fluid Management
CLV	Ares Crew Launch Vehicle
CSA	Customer Supplier Agreement
CxP	Constellation Program
EDS	Earth Departure Stage
ESAS	Exploration Systems Architecture Study
ETDP	Exploration Technology Development Program
EVA	Extra Vehicular Activity
GRC	NASA Glenn Research Center
ISRU	In-Situ Resource Utilization
LAT	Lunar Architecture Team
PCAD	Propulsion and Cryogenics Advanced Development
PDR	Preliminary Design Review
RCS	Reaction Control System
SE&I	Systems Engineering and Integration
SOA	State of the Art
SRR	Systems Requirements Review
TBR	To Be Resolved
TRL	Technology Readiness Level
VSE	Vision for Space Exploration

I. Introduction

The NASA Vision for Space Exploration (VSE) includes human space flight missions to the International Space Station, the Moon, and Mars. To accomplish the VSE, several iterations of architecture studies and concept development have been completed. The Exploration Systems Architecture Study (ESAS) completed and published in December of 2005 included a detailed transportation architecture for all three missions, which was subsequently refined. The Lunar Architecture Team (LAT) study, published in December of 2006, focused on defining the surface architecture and detailed drivers for lunar surface operations. At the writing of this paper, a follow-on study, LAT-2 is nearing completion to refine the architecture further. Each of these mission concepts identified technology that was required to "enable" the mission concepts, as well as technology that was highly desired to "enhance" the mission. Technology solutions enable missions by buying down the risk on mission performance, life-cycle costs, and/or safety and reliability. In an ideal situation, NASA would fund all technologies that had promise of payback for later missions. However, fiscal realities are such that only the highest priority subset of the technologies identified can be funded and this decision process is a significant challenge. Perhaps more importantly, there are many factors that influence the ability to successfully infuse any technology including the technical risk, requirement and development schedule maturity, and, funds available. This paper focuses on the successful infusion processes that have been used recently for the technologies in development for the lunar exploration flight program, Constellation. One technology project, Propulsion and Cryogenics Advanced Development (PCAD), has implemented an effective technology infusion process with the Lunar Lander flight project. A similar process was recently applied across the power technology needs starting with the Energy Storage Project. With the help of ETDPO, other successful technology projects, and the Constellation customers, an effective technology infusion process is now in implementation across the program. With the VSE, there is an unprecedented opportunity to make this technology infusion a success because of the strong "technology pull" to enable the missions.

II. Vision for Space Exploration Architectures

The Exploration Systems Architecture Study (ESAS) completed in December 2005 included a lunar transportation architecture as shown in figure 1.

This architecture was updated and modified through follow-on studies including the Lunar Lander internal study concepts and the Lunar Architecture Team. For example, the Lander key design drivers were to minimize mass of the descent and ascent stages to allow the maximum payload possible, and, to simplify the interfaces.

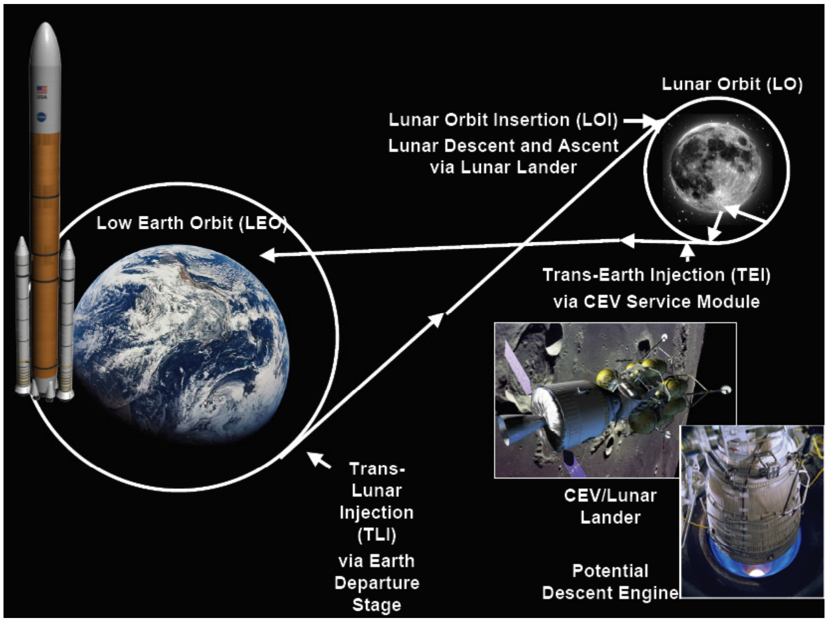

Figure 1.—Exploration Transportation Architecture

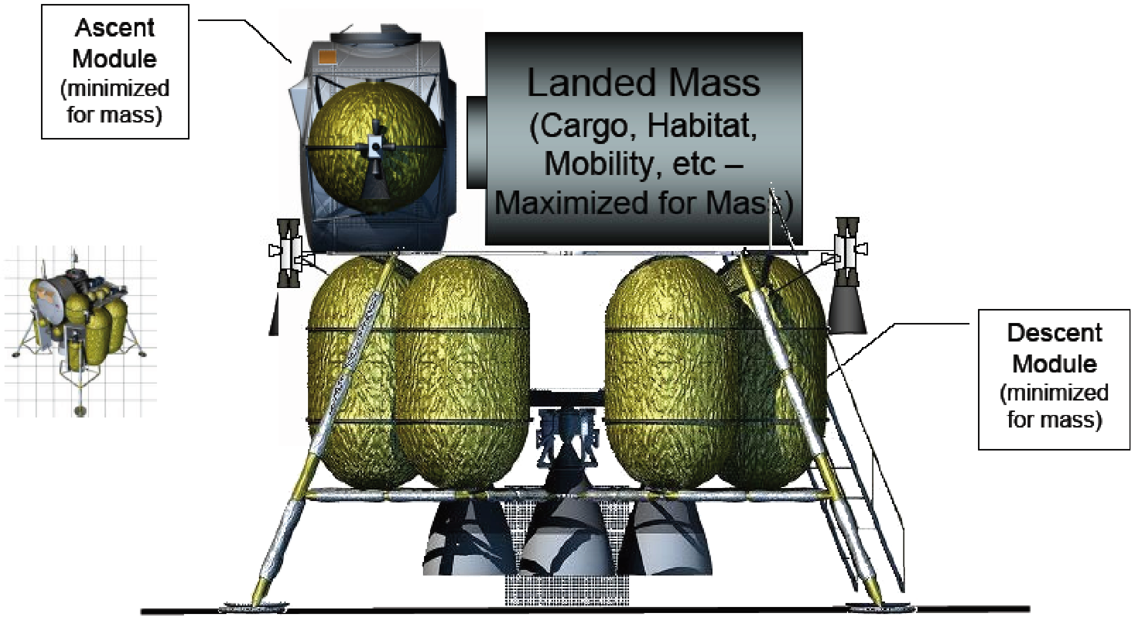

Figure 2.—Notional LAT Lander Concept

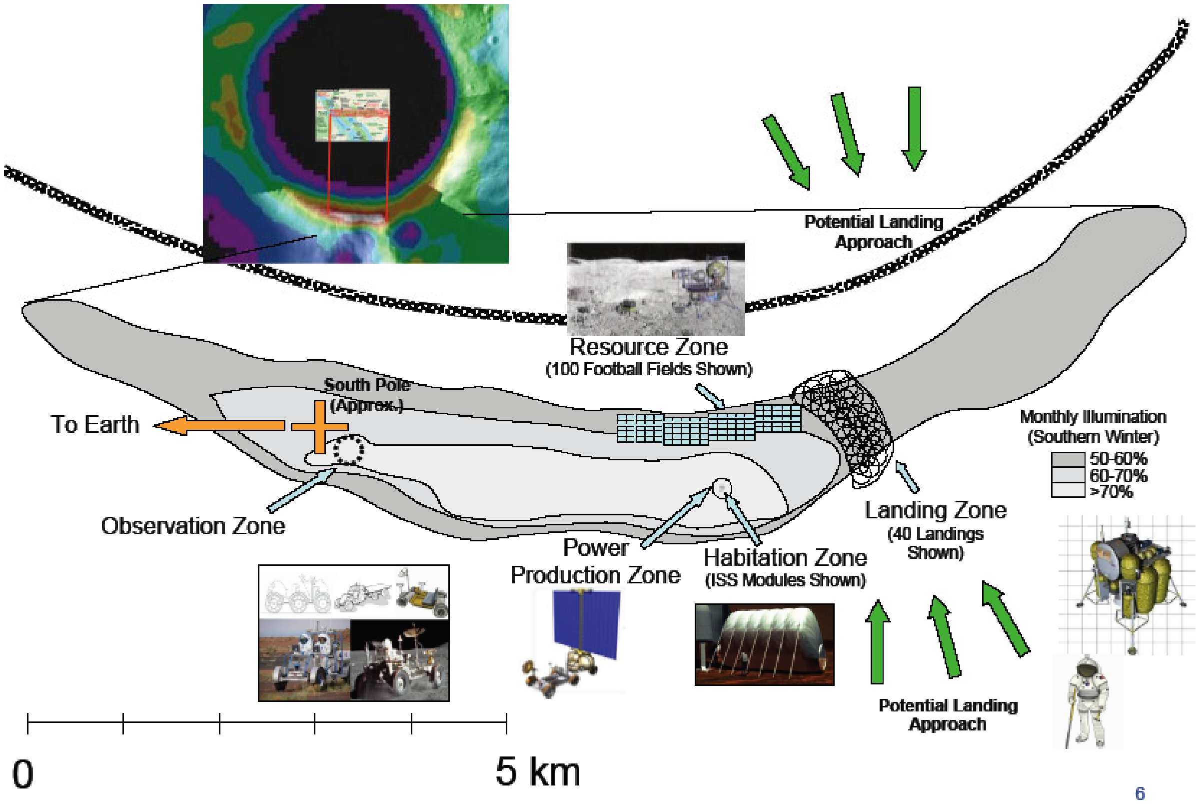

Figure 3.—Notional LAT Surface Architecture Concept

In addition to the Lunar Lander, based on the objectives defined for the lunar missions, a surface architecture was defined including surface power, surface communications, habitats, rovers for humans and science, and in-situ resource utilization. A notional architecture is shown in figure 3.

III. Architecture Driven Technology Needs

The architecture studies described above each precipitated a time-phased list of technology needs required to achieve the architecture concept of operations. The ETDP was formulated to address these technology needs. The current program consists of 21 technology projects, most containing multiple technologies within each project, each addressing one or more elements of the future flight systems as depicted in table 1.

TABLE 1.—TECHNOLOGY MAPPING TO CONSTELLATION FLIGHT ELEMENTS

			Launch Vehicle					Lunar Surface Systems						
Discipline	**Technology Project / Constellation Flight Element**	**Orion (CEV)**	**ARES-I (CLV)**	**ARES-V (CaLV)**	**EDS**	**Lunar Lander**	**EVA**	**Power**	**Habitat**	**Mobility**	**ISRU**	**Comm**	**Cross-cutting/ Outpost**	**Ground or Flight Ops/ SE&I**
Mechanical	Structures, Materials, & Mechanisms	●	●		●	●			●	●	●			
Protection Systems	Thermal Protection Systems	●												
	Dust Management					●	●	●	●	●	●	●	●	
Propulsion	Propulsion and Cryo Advanced Development	●				●								
	Cryogenic Fluid Management	●			●	●					●		●	●
Power	Energy Storage (Batteries & Fuel Cells)			●		●	●	●		●	●	●	●	
	Advanced Fission Surface Power							●					●	
Thermal	Thermal Controls	●				●	●		●	●	●		●	
Avionics & Software	High Performance & Rad Hard Electronics	●				●	●					●	●	
	Integrated System Health Management		●											
	Automation for Operations													●
	Intelligent Software Design	●												●
	Autonomous Precision Landing					●								
	Automated Rendezvous & Docking Sensor	●												
Environmental Control & Life Support	Exploration Life Support	●							●				●	
	Environmental Monitoring and Control	●				●			●				●	
	Fire Prevention, Detection & Supression	●				●			●					●
Crew Support	Extra Vehicular Activity (EVA)						●							
ISRU	In-Situ Resource Utilization										●		●	
Robotics, Operations and Supportability	Supportability												●	●
	Human-Robotic Systems									●			●	

IV. Technology Prioritization

The technology areas in table 1 represent technology needs identified by the general architecture assessments such as ESAS and LAT. This identification as a promising technology in architecture assessments is a necessary but not sufficient condition to remain funded. The Constellation Program (CxP), who manages the development of the Exploration flight elements, in concurrence with NASA Headquarters and the ETDP, has implemented a Technology Prioritization Process (TPP)[1] to assess and prioritize the technology needs across the program. The CxP process includes rigorous systems engineering assessments to identify and prioritize the technology capabilities required to meet the design, development, and test of mission systems, going beyond the initial architecture assessments. These capabilities are identified by mission phase (Initial/ISS, Lunar, or Mars) and by "enabling" or "enhancing." In this context, the mission cannot be completed without the enabling technology. However, the enhancing technologies allow missions with better performance and/or lower risk and life cycle costs. The net result is an integrated technology priority list identifying the "pull technologies." In the case where flight system requirements are not well defined, the technology program works with the architecture concept leads to define core

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[1] Constellation Program Technology Insertion Strategy Document, CxP 70079

technologies that cross most architecture solutions, working to supplement the TPP process. For example, although the exact mobility needs are not known for the surface we know that low power, lunar environment tolerant (e.g., dust, vacuum, temperature) mobility subsystems are required to be developed.

V. Technology Infusion Process

At the macro scale, a technology may have been identified as critical and selected for funding based on the program priority list. Although a technology development has sufficient funding and some level of success with development, it may not be used in the target flight system, or “infused.” There are many factors that influence the ability to successfully infuse any technology including the technical risk, requirement and development schedule maturity, and funds available. An effective infusion process has been demonstrated by the ETDP PCAD Project, managed at GRC. The PCAD project content includes “green propulsion” (non-toxic) main and reaction control system (RCS) propulsion, currently including hydrogen and methane fuels. PCAD also includes Cryogenic Fluid Management (CFM) content including storage, distribution, and low gravity management of cryogenic fluids for vehicles and surface systems. PCAD’s process started with a sound risk development plan and was completed with an integrated project plan, including content, schedule and cost. The following are details of the infusion process that recently worked well between the PCAD and the Lunar Lander Projects.

A. Baseline Requirements and Definitions

To start the infusion process, the needs, goals, and objectives of the flight program need to be stated in a set of requirements. For PCAD, although the Lander did not have baselined requirements they were able to confirm the majority of the requirements to guide the technology development. An example of those requirements is for the Lander liquid oxygen (LOx), liquid methane ascent main engine as shown in table 2.

TABLE 2.—EXAMPLE OF LANDER LOx-METHANE ASCENT MAIN ENGINE PRELIMINARY REQUIREMENTS

Performance	Life	Propellant inlet conditions
Total thrust: 3,500 to 7,500 lbf (TBR)	6 starts (TBR)	Pressure: 325 psia
Isp: 355 sec minimum End of Life	9 months in space (TBR)	Temperature: 185 °R
Start time: 0.5 sec (max)	Impulse (includes 1.5x margin)	
Vacuum start	Continuous:4,500K lbf*sec (650 sec @ 7.5K) (TBR)	LOx temperature: 163 to 224 °R with a goal down to 145 °R
	Continuous:4,500K lbf*sec (1425 sec @ 7.5K) (TBR)	LCH$_4$ temperature: 170 to 224 °R with a goal up to 264 °R
	Sun and deep space viewing	Startup vapor slug: 100 in.^{3}

In addition to requirements, there must be an understanding and definition of what Technology Readiness Level (TRL)[2] means for a given technology. For example, in general Exploration has a goal to develop technologies to a TRL level of 6 before they are delivered to the flight program for engineering development. For propulsion and CFM, PCAD spent significant time to define what TRL meant for their disciplines. In general, most technologies have a range of infusion points that follow the maturity of the flight design. For example, at SRR the technology development may not be complete; however, enough risk mitigation has been accomplished to adequately address the design maturity and risk.

B. Technology Risk Assessment

The PCAD Team conducted a risk workshop to identify the risks to be able to meet the Lunar Lander and CEV propulsion system requirements. A rigorous risk identification process was used to enable succinct statements of the risk, a relative ranking, mitigation strategies, and ultimately customer ownership. These risks serve to identify the technology gaps compared to State of the Art (SOA). The workshop provided raw data that needed to be consolidated for each area. This process resulted in a prioritized set of risks for the Lander propulsion system as shown in table 3. The color-coding for the risk corresponds to the scoring of likelihood (1-5) multiplied by consequence (1-5). Reds are 15-25; yellows 8-12 and greens are <8. The PCAD Risk abbreviations are “G” for green propulsion (e.g., methane fuel), “C” for CFM and, “D” for deep-throttling main engines. For example, the first

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[2] TRL levels as defined in the NASA White Paper “Technology Readiness Levels” by John C. Mankins, April 1995.

risk in the table, G15 was 15th risk at the workshop for green propulsion and it covered ignition reliability for liquid oxygen-liquid methane combination. Customer interaction at the actual workshop was limited, hence follow-up meetings were held with the customer to review and refine the risks and associated mitigation strategies, and to effectively transfer ownership of the risks.

TABLE 3.—PCAD ROLLED-UP RISKS FOR LUNAR LANDER (NOT IN ORDER)

Lunar Lander Risk	Risk Statement	Corresponding PCAD Green Propulsion Risk
RCS & Ascent Engine Ignition	Given that LOX/Methane are non-hypergolic propellants, an ignition system is required; Because no space qualified hardware currently exists for LOX/Methane there are risks that the required ignition systems will not be at a TRL of 6 prior to full-scale development.	G15 - Ignition Reliability G31 - Lack of Space Qualified Exciters G30 - Lack of Qualified Spark Plug for High Cycle Applications C088 - Propellant Acquisition G35 - RCS Igniter Integration with Main Stage
LOX/Methane Propulsion Technology Maturity	Given that flight-qualified, human-rated LOX/Methane propulsions systems do not currently exist, there is a limited amount of data at both the component and system level to guide mission planning and provide confidence the systems will meet performance targets.	G02 - Integrated System Test Requirement C051 - CFM System Level Integration G26 - Lack of Performance Data to Benchmark Analytical Models G36 - Performance Loss Due to Propellant Quality G09 - Material Limits at High Temperature Operation G29 - Propellant Delivery Timing & Valve Operations G19 - Thermal Cycle Limits of Thrust Chambers G17 - Combustion Stability Characteristics G06 - Engine Health Monitoring
Unknown Ascent/RCS Propulsion System Requirements	Given that advanced development of LOX/Methane propulsion technology is proceeding prior to establishment of LSAM ascent and RCS requirements; there is a risk that the advances made through PCAD will not satisfy these future requirements. Alternatively, if advanced development is to satisfy a very wide range of potential requirements there is a risk that PCAD resources & schedule are inadequate.	G27 - Variable Requirements G25 - Start Transient Requirements G37 - Heat soakback requirements G50 - Thermal Exposure Variations G22 - Propellant Specification
LOX/Methane Test Facility Suitability & Availability	Given that there are limited contractor and government test facilities currently supporting a range of Cx propulsion system development activities; there is a risk that necessary advanced development tests cannot be accomplished when needed.	G4 - Lack of Facility capabilities and/or availability
LOX/ H2 Ascent Engine Fast Start	Given that a pump fed LOX/ H2 engine is being considered for LSAM Ascent and the engine has a requirement to be able to perform during certain abort scenarios, there is a possibility that it might not meet the engine quick/fast start requirements for the abort.	D95 - LOX/ H2 Ascent Engine Fast Start
Descent Engine Performance	Given the propulsion needs for high performance, reliable lunar descent, there is a risk that this capability cannot be met using an engine design within the current technology base (RL-10 derivative).	D91 - Inconsistent Assumptions Between Performance, Cost & D101 - Deep Throttle Engine Overall Performance D104 - Deep Throttle Engine Human Rating D-97 - Deep Throttle Engine, Unclear Requirements
Descent Deep Throttling	Given that the lunar descent propulsion will need engines to provide a wide range of thrust, there is a risk that throttling requirements cannot be met.	D89 - Deep Throttle Engine Throttling D94 - Deep Throttle Engine Specific Impulse D102 - Deep Throttle Transient Response D108 - DTE Expander Cycle Heat Transfer D88 - DTE Terrain Avoidance Maneuvers D107 - DTE Expander Cycle Heat Output D90 - DTE Engine Restart After Cold Soak D106 - DTE Chug Stability D109 - DTE Chamber Durability D93 - DTE Weight D103 - DTE Burn Time and Restart
Descent Engine Development Base	Given that there is limited expertise within both NASA and industry, successful on-schedule descent engine development is at risk.	D112 - Limited Number of Qualified Suppliers for Deep Throttle Engine D113 - Limited In-House Technical Competency
Cryogenic Propellant Quality	Given the nature of a distributed cryogenic propulsion system, there is a risk that engine feed quality will be unacceptable.	C053 - RCS Feed line C088 - Propellant Acquisition
Active Cooling for Thermal Control	Given that long duration liquid hydrogen storage is required, active thermal control may be required to mitigate boil-off.	C090 - Long Term In-Space Cryogenic Propellant Storage C065 - Active Cooling for Thermal Control
Cryogenic Fluid Management Technology Maturity	Given that flight-qualified, human-rated long duration, on-orbit cryogenic fluid management systems do not currently exist, there are advanced development tasks at both the component and system level that have not yet been completed.	C090 - Long Term In-Space Cryogenic Propellant Storage C091a - COPV for Cryogenic Propellants C091b - COPV for High Pressure Helium C092 - CFM Development Risk C051 - CFM System Level Integration C089 - Low Gravity Mass Gauge C072 - Cryogenic Helium Regulator
Lunar Dust Contamination	Given that the LSAM will be exposed to lunar dust, there is a risk that contamination could result in malfunctions	D105 - LOX/ H2 Ascent Engine Contamination Due to Lunar Dust C064 - Lunar Surface Thermal Control G39 - Foreign Object Damage from Lunar Surface

C. Integrated Technology and Flight Schedules

Based on the integrated risk matrix that was reviewed by the Lander, schedules for the technology development were developed to meet the flight project schedule. The risk mitigation items became tasks on a schedule supporting the Lander SRR and PDR, and some times post-PDR phases. Each task included an associated resource estimate. Several iterations were conducted to optimize the tasks (e.g., synergy was found by assuming the same reaction control system for the Ascent and Descent Stages). Throughout the process, all participants maintained a strict rigor to challenge task needs by inserting only mandatory tasks that met Lander schedule and critical risk mitigation needs. Based on the risk priorities and phasing of funding, the content within the planned budget and outside of the guideline was identified. Further iterations and scrubs of the task schedule were conducted to minimize the overguideline needs. By the end of this meticulous process, the Lander Project became the best advocate for the increased funding needs.

D. Final Steps of Technology Infusion

The final step in the process was the documentation of the PCAD technology deliverables to the Lander Project. This was accomplished with a Customer Supplier Agreement (CSA),[3] including the technology development schedule of deliverables to meet the flight schedule needs, as shown in table 4. Over time, the Lander Project has continued to refine their requirements; however, the original PCAD risks were and still are applicable. The CSA with PCAD and the Lander Project, and the associated development schedule will remain a "living document" with periodic updates (at least once/year) to assure the alignment for technology infusion. Updates will also be required as the funding changes. The process outlined here, including a rigorous risk development process, enables a more stable development program that can adapt to changes.

TABLE 4.—PCAD AND LUNAR LANDER SCHEDULE FOR TECHNOLOGY DELIVERABLES

Deliverables	Expected completion date	Description
PCAD—Ascent/Descent RCS Design Deliverables		
NGST RCS Contract	4th Qtr FY07	Complete workhorse testing of RCS concept. Test Report
Aerojet RCS Contract	1st Qtr FY08	Deliver 4 Aerojet 100-lbf RCS engines (Contract Option 3)
Igniter Duration Testing (Duration and Wide Operating Range)	1st Qtr FY08	Vacuum ignition pulse (100,000+) duration testing
High Area Ratio Testing	3rd Qtr FY08	Vacuum testing of a single engine to obtain performance data and benchmark data to examine kinetics models in existing analytical tools
Spark Plug Durability	4th Qtr FY08	Heat transfer analysis and thermal stability analysis and test data of current insulating materials in LOx/LCH_4 environment
100-lbf LOx/LCH_4 RCS Thruster Sea Level Testing	4th Qtr FY08	Sea level testing over a range of propellant inlet conditions
100-lbf LOx/LCH_4 RCS Thruster APSTB	1st Qtr FY09	Vacuum testing of a 3 thruster reaction control box in a CEV configuration
Exciter Breadboard demonstration	3rd Qtr FY09	Breadboard testing of capacitive and/or inductive discharge Ignition proof-of-concept (PoC) exciter designs
100-lbf LOx/LCH_4 RCS Thruster Vacuum Testing	4th Qtr FY09	Thermal vacuum testing over a range of propellant inlet conditions
LOx/LCH_4 RCS Thruster APSTB	4th Qtr FY11	Testing of RCS engines and main engine simulator in lunar lander APSTB configuration.
PCAD—Ascent Main Engine Deliverables		
KTE Workhorse Testing	3rd Qtr FY07	Complete sea level workhorse testing of 7.5K-lbf LOx/LCH_4 main engine concept. Test data report.
KTE Contract	4th Qtr FY07	Complete contract base period with PDR for 3.5K-lbf LOx/LCH_4 prototype Ascent Main Engine. Workhorse test date and PDR level engine design.
ATK Contract	4th Qtr FY07	Complete contract base period with PDR for 3.5K-lbf LOx/LCH_4 prototype. Ascent Main Engine. Workhorse test date and PDR level engine design.
PWR Heated Tube SAA	4th Qtr FY07	Complete testing with super heated gaseous methane and subcooled liquid methane - Test Results.
Workhorse vacuum testing	1st Qtr FY09	Complete vacuum workhorse testing of LOx/LCH_4 main engine concept. Test data report
ATK Workhorse Testing	3rd Qtr FY11	Complete sea level workhorse testing of 7.5K-lbf LOx/LCH_4 main engine concept. Test data report.
Prototype engine demonstration	1st Qtr FY12	Complete design, development, fabrication and vacuum testing of a lunar lander prototype ascent engine.

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[3] CSA is part of the Cx Technology Insertion Strategy document, CxP 70079

E. Other Technology Projects

Other GRC ETDP Projects have enjoyed some success following the lead of PCAD. At the time of this writing, a Power Risk Workshop is planned for late August 2007 to identify the power technology risks for the Energy Storage and the Fission Surface Power Projects. This risk workshop and risk mitigation identification process will enable more rigorous integrated schedules and CSA's with the Lander, EVA, and various Lunar Surface Systems. The Dust Management Project is in formulation and is planning to utilize this process.

VII. Summary

Historically it has been difficult to successfully infuse new technologies into flight systems. The Exploration Program, with the help of the Architecture Study teams, the ETDP and the Constellation Program, has developed a method to prioritize and manage the technology portfolio for the Agency. At a technology project level, this paper showed the details of an effective technology infusion process that was used by the ETDP PCAD Project, and is now in use by other technology projects. The driving process is based on rigorous risk assessments, which change only when the overall architecture changes, enabling some level of stability in the process to be able to accommodate the typical perturbations of most NASA programs, including budget fluctuations.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01-01-2008	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE A Successful Infusion Process for Enabling Lunar Exploration Technologies	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Over, Ann, P.; Klem, Mark, K.; Motil, Susan, M.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 825855.01.03.03
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-16228
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITORS ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2008-215045; AIAA-2007-6196

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 16 and 18
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The NASA Vision for Space Exploration begins with a more reliable flight capability to the International Space Station and ends with sending humans to Mars. An important "stepping stone" on the path to Mars encompasses human missions to the Moon. There is little doubt throughout the stakeholder community that new technologies will be required to enable this Vision. However, there are many factors that influence the ability to successfully infuse any technology including the technical risk, requirement and development schedule maturity, and funds available. This paper focuses on effective infusion processes that have been used recently for the technologies in development for the lunar exploration flight program, Constellation. Recent successes with Constellation customers are highlighted for the Exploration Technology Development Program (ETDP) Projects managed by NASA Glenn Research Center (GRC). Following an overview of the technical context of both the flight program and the technology capability mapping, the process is described for how to effectively build an integrated technology infusion plan. The process starts with a sound risk development plan and is completed with an integrated project plan, including content, schedule and cost. In reality, the available resources for this development are going to change over time, necessitating some level of iteration in the planning. However, the driving process is based on the initial risk assessment, which changes only when the overall architecture changes, enabling some level of stability in the process.

15. SUBJECT TERMS
Lunar; Exploration; Technology development; Propulsion; Energy storage

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	14	**19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390