Experiences in Managing the Prometheus Project

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Abstract — Congress authorized NASA's Prometheus Project in February 2003, with the first Prometheus mission slated to explore the icy moons of Jupiter. The Project had two major objectives: (1) to develop a nuclear reactor that would provide unprecedented levels of power and show that it could be processed safely and operated reliably in space for long-duration, deep-space exploration and (2) to explore the three icy moons of Jupiter – Callisto, Ganymede, and Europa – and return science data that would meet the scientific goals as set forth in the Decadal Survey Report of the National Academy of Sciences.

Early in Project planning, it was determined that the development of the Prometheus nuclear powered Spaceship would be complex and require the intellectual knowledge residing at numerous organizations across the country. In addition, because of the complex nature of the Project and the multiple partners, approaches beyond those successfully used to manage a typical JPL project would be needed. This paper[1] will describe the key experiences in managing Prometheus that should prove useful for future projects of similar scope and magnitude.

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1. INTRODUCTION

The Prometheus Project was an element of the NASA Prometheus Nuclear Systems and Technology Theme. Note that when the NASA Associate Administrator for Space Science authorized the Project in March 2003, the Project was known as the Jupiter Icy Moons Orbiter (JIMO) Project; pre-project work for JIMO was performed under the NASA Nuclear Systems Initiative.

NASA headquarters developed the JIMO level-1 requirements, which tasked the Project to develop a Deep Space Vehicle (DSV) for outer solar system robotic exploration missions. The DSV would combine a safe, reliable, space nuclear reactor with electric propulsion. In addition, the Project was to execute a scientific exploration mission to the icy moons of Jupiter (Callisto, Ganymede, and Europa). In support of these requirements, the Project was to develop mission-unique science elements, collectively called the Mission Module. This was responsive to the National Academy of Sciences' Decadal Survey report, which declared Europa exploration to be the number one priority for a planetary exploration "flagship mission" for the coming decade. This mission would have been performed by the Spaceship (combining the DSV with the Mission Module) and the Ground System mission support capabilities.

Technical Challenges and Team Building

Prometheus would have enabled a new era of space exploration through increased spacecraft maneuverability and unprecedented amounts of on-board electrical power for propulsion and science. Significant improvements would have been made in scientific measurements (enabling the use of high-capability instruments), mission design options (including successive orbits of multiple solar system bodies), and telecommunications capabilities (allowing for unprecedented amounts of scientific data returned from deep space). Development of this capability necessitated significant technology advances in seven areas:

(1) Space nuclear reactor.

(2) Energy conversion.

(3) Heat rejection.

(4) Electric propulsion.

(5) High-power telecommunications.

(6) Radiation-hardened components.

(7) Low-thrust trajectory and navigation tools.

These technical challenges created a corresponding management challenge. Because no one organization possessed all of the requisite expertise, capabilities, and resources to design, develop, launch, and operate the Spaceship and perform JIMO and other exploration missions, a multi-organizational team was needed.

Soon after project initiation, the team began internal trade studies (Technical Baseline 1, completed in August 2003) and initiated technology planning and development

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activities. In April 2003, three industry-led teams were placed on contract to perform trade studies and, later, conceptual design studies.

In January 2004, President Bush announced the Nation's Vision for Space Exploration, including the development of power generation and propulsion capabilities for exploration. In February 2004, the NASA Administrator established the NASA Exploration Systems Mission Directorate (ESMD) and transferred Prometheus into ESMD. The following month, the Secretary of Energy assigned the lead for development and delivery of civilian space nuclear power systems to Department of Energy's (DOE's) Office of Naval Reactors (NR).

Also in 2004, NR established the Naval Reactors Prime Contractor Team (NRPCT) and the industry teams delivered their Final Reports. In May 2004, JPL issued the industry down-selection Request for Proposal (RFP) for the Spacecraft Module (defined as the DSV minus the reactor); the source selection process, which resulted in the selection of Northrop Grumman Space Technologies, Inc. (NGST), was completed in September 2004.

Led by NASA's Jet Propulsion Laboratory (JPL), the assembled Project team included NRPCT, five NASA Field Centers, NGST, and a number of supporting DOE laboratories, universities, and industrial subcontractors.

Prometheus Development Process

Prometheus was to be developed consistent with the NASA life cycle for flight projects according to the following schedule:

(1) Pre-phase A (Advanced Studies): Nov. 2002 – Feb. 2003 (with precursor studies starting in Sept. 2002) (Completed)

(2) Phase A (Mission and Systems Definition): Mar. 2003 – Sept. 2005 (Completed)

(3) Phase B (Preliminary Design): Oct. 2005 – Sept. 2008

(4) Phase C/D (Design, Build and integrate): Oct. 2008 – July 2015

(5) Phase E (Operations): Aug. 2015 – Sept. 2025

The Project successfully completed Phase A, passing the JPL Project Mission and Systems Review (PMSR) in July 2005. Supporting this review was the Prometheus reference Spaceship design and project life cycle cost estimate, 68 "gate product" documents, and an extensive library of other documentation.

Project Cancellation

In August 2005, NASA re-evaluated its priorities in light of available funding and established Return to Flight, the International Space Station, and the Crew Exploration Vehicle as the highest priority tasks for the Agency. The Agency's nuclear initiatives were, therefore, postponed to a large extent, and work within the nuclear systems program was reprioritized. Nuclear Electric Propulsion (NEP) was given third priority behind nuclear surface power and nuclear thermal propulsion. Consequently, the Prometheus Project was directed to not proceed into Phase B.

The Project was officially discontinued in October 2005. A summary final report of Prometheus was developed as documented in the reference.

Paper Overview

This paper will discuss the management challenges associated with the Prometheus Project. The paper includes both the challenges that were directly related to the multiple partners associated with the Project and the implementation of the management practices that proved to be most effective. To understand why it was not possible to have Project participants operate in isolation, readers must have an understanding of the close, interactive nature of the needed technology, of the mission design, and of the hardware/software performance requirements. Therefore, the paper also discusses the technical challenges.

2. TECHNOLOGY

The primary technology objective was to demonstrate safe and reliable operation of a NEP system in space. This required, first and foremost, the development of advanced nuclear and materials technologies needed to construct and operate a long-life space nuclear reactor.

In addition to the development of the space nuclear reactor technologies, several other technology developments were necessary to meet the Prometheus Project objectives.

The Project invested in the development of power conversion and heat rejection technologies. The development of a power conversion system was necessary to enable conversion of the thermal energy generated by the reactor into useful electrical power for propulsion, scientific instrumentation, and high-data-rate communications. Because not all of the thermal energy generated by the reactor could be effectively converted into electrical power, development of an advanced heat rejection system was also needed.

Although electric propulsion has been used previously by both NASA and the commercial satellite industry, additional technology development activities were needed by the Project to meet the high-power, long-life requirements of deep space missions

The intense radiation environment produced by the on-board reactor and the high-radiation environment of the Jovian system required the Prometheus Project to undertake a significant radiation hard electronics technology development effort.

High-power telecommunications technologies were also being developed by the Project to meet the high data rate and high data volume requirements needed for science.

Detailed technology development plans, including maturity criteria, development milestones, test and verification plans, and qualification needs were developed to support the Project schedule. A detailed summary of the technology development results from Prometheus is contained in the reference.

3. JIMO Mission Overview

The Prometheus Project was charged with developing a DSV that could be used in conjunction with mission-specific Mission Modules (including both hardware and software) and have the capability for use on multiple deep space mission applications.

The primary elements of the JIMO mission consisted of a JIMO Spaceship, three launch vehicles, two transfer vehicles, and the ground-based science and engineering operations teams and facilities. The JIMO Spaceship is comprised of a Prometheus DSV carrying a JIMO-unique Mission Module.

Figure 1 shows the mission overview timeline with the major events and phases, based on the Reference Trajectory completed in the summer of 2005.

The JIMO launch campaign was to open in May 2015 and required three separate launches followed by rendezvous and docking of the separate components in Earth orbit prior to interplanetary injection. As NASA had not selected the launch vehicle(s) to be used by JIMO, the delivered mass capabilities as well as other key planning characteristics were analyzed parametrically. The baselined launch campaign assumed a 37,000-kg launch vehicle capability to an altitude of 407 km at 28.5 degree inclination. That orbit was called the Earth Assembly Orbit. This orbit was chosen as a compromise that provides a large payload to orbit balanced against the need to have sufficient lifetime against atmospheric decay to accomplish all the rendezvous/docking operations.

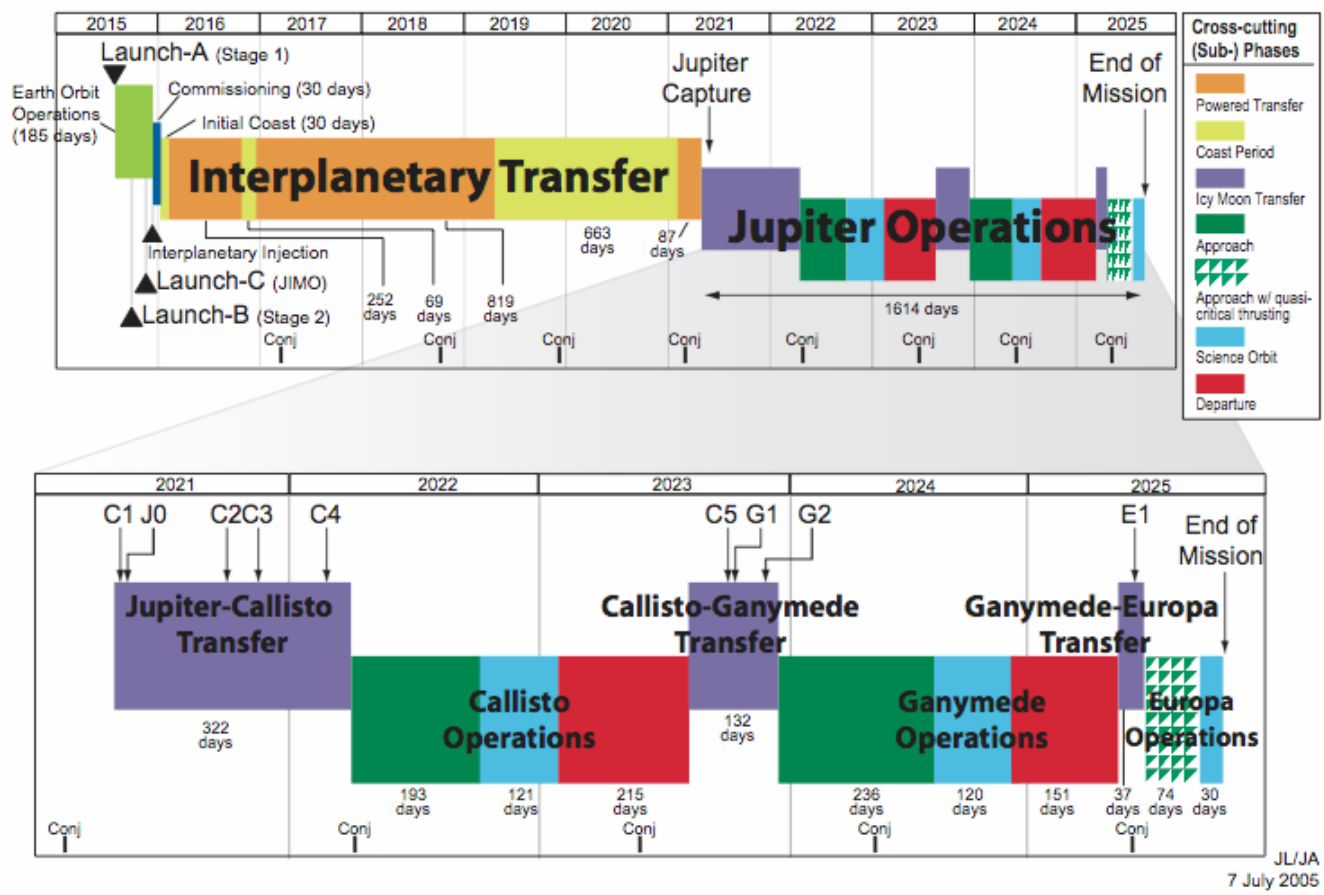

Figure 1 - Mission Overview.

The successful launch of the first transfer vehicle would have initiated the start of the Earth-Orbit Operations phase, during which the subsequent launches, the rendezvous and docking, and interplanetary injection were planned. Subsequently, the second transfer vehicle was to be launched to an orbit that was similar to that of the first transfer vehicle. Upon successful rendezvous and docking of the transfer vehicles with each other, the JIMO Spaceship was planned to be launched as early as September 2015 into that same Earth Assembly Orbit. The docked transfer vehicles would subsequently rendezvous and dock with the Spaceship.

The JIMO Spaceship would spend up to one month in Earth orbit, either on its own or attached to the transfer vehicles, depending on the orbit phasing necessary to achieve the Earth-departure trajectory targets. As early as October 2015, the Spaceship would inject onto an interplanetary trajectory (C_3 of 10 km^2/s^2). The injection period would end in mid-January 2016.

To understand the implications on operational limitations and fault protection requirements, operational scenarios for each phase of the mission were developed by the Project team. A top-level description of the scenarios follows.

Commissioning

The purpose of the commissioning phase was to transition JIMO from an undeployed, solar-powered Spaceship configuration to a configuration in which the space nuclear reactor is powering the Spaceship and routine electric thrusting can begin. Commissioning would involve four major activities:

(1) Deployment of the main spacecraft booms and radiators and jettisoning of the aeroshell (which would have ensured the physical integrity and safety of the reactor in the event of an unplanned re-entry prior to achieving a stable Earth orbit).

(2) Heat rejection, power conversion, and reactor startup.

(3) The activation and checkout of the electric propulsion system.

(4) Jettisoning of the docking adapter and the completion of the science hardware deployment.

The commissioning phase was anticipated to take 30 days.

Interplanetary Transfer

The baseline trajectory was a low-thrust (resulting from the use of the highly efficient ion-engines), direct trajectory to Jupiter with three major thrusting arcs. The first and second arcs were separated by a short coast period near the first aphelion, and were planned to send the Spaceship out toward the orbit of Jupiter.

After roughly a year of coast, the Spaceship would approach Jupiter's orbit, and it would begin the rendezvous thrust arc, which was timed so as to allow capture of the Spaceship by Jupiter several months later.

Jupiter Operations

Jupiter operations were planned to begin 60 days prior to Jupiter Closest Approach (JCA). Capture by Jupiter would occur roughly a month prior to JCA. During this approach, the Spaceship would take optical navigation images of Jupiter, Callisto, and the other Galilean moons against star backgrounds to significantly improve the knowledge of Jupiter and its satellites' ephemerides. The Spaceship would spend over four years in the Jovian system. During that time, it would spend several months in the vicinity of each of the icy Galilean moons, eventually orbiting them in turn, starting with Callisto, followed by Ganymede, then Europa.

The Spaceship would be thrusting much of the time, and fields and particles science data would be gathered, when possible, subject to thrusting constraints. A systematic Io observing campaign was also planned to be conducted by selected remote sensing instruments, again subject to constraints on attitude.

Transfer phases would separate the satellite operations phases (see Figure 1). The satellite operations phases were broken into Approach, Science Orbit, and Departure sub-phases. Due to the weak control authority of the low-thrust propulsion system and the strong gravitational perturbations caused by the multi-body environment, the sensitivity of the trajectory to missed thrust can be quite high during the Approach and Departure sub-phases. At certain times during the Europa Approach phase, the instantaneous orbit lifetime (defined as the time prior to escape or impact if thrusting were lost) would be as short as a few hours for optimum delta-V transfers. Constraints on the mission design and possible special robustness requirements on the Spaceship and/or mission operations teams were required to safely deal with these sensitivities. For example, higher-thrust Hall thrusters were added specifically for higher control authority during the Europa Approach phase.

The Approach sub-phase was planned to end with the Spaceship in the baseline science orbit: near-polar inclination, at a near-circular altitude orbit of 100 to 200 km, and at a node that provided appropriate lighting coverage for the optical instruments. Satellite orbit-stay durations were required (threshold values) to be 60 days at Callisto and Ganymede and 30 days at Europa. A goal (objective values) of twice the requirement was sought, although the radiation environment at Europa would make such a goal difficult to attain. End of mission was planned with the Spaceship in science orbit at Europa.

4. SPACESHIP

The Spaceship concept is shown in Figure 2. The wet mass of the Spaceship, including a 1500-kg allocation to the Mission Module and 12,000 kg of Xenon propellant, was estimated to be 36,375 kg. This mass included a 30% mass margin, as well as specific allocations for design growth allowance. The deployed length of the Spaceship was ~58-m long, with a radiator area of 422 M^2.

The forward end of the Spaceship was comprised of a high temperature gas-cooled reactor directly coupled with redundant Brayton turbo alternators for power conversion with the capability of producing approximately 200 kW of electrical power. A radiation shield was just aft of the reactor; this shield provided a conical shadow for reactor radiation attenuation to the remainder of the Spaceship. Control and monitoring for the reactor would be provided by the reactor instrumentation and control, with elements located both in the vicinity of the reactor and in protected areas of the spacecraft bus.

Aft of the reactor and power conversion elements was the Spacecraft Module, the configuration of which was dominated by a ~43-m long main boom assembly. This boom was used to provide a mounting structure for the radiator panels of the heat rejection system, necessary to dispose of waste heat from the reactor. The main boom was also sized to provide a separation distance of electronic components housed in the spacecraft bus from the reactor, resulting in reduced requirements for the reactor radiation shield. At the aft end of the boom was the spacecraft bus, which contained the majority of the electronic subsystems needed to control and operate the DSV. Main propulsion was provided by Ion thrusters (with a specific impulse of ~7000 seconds) and Hall thrusters mounted on two deployable thruster pods, making up the Electric Propulsion Segment of the Spacecraft Module. A spacecraft-docking adapter was also included in the Spacecraft Module to support early on-orbit operations and docking with the interplanetary transfer stages. The docking adapter provided power, communications, and attitude control functions for the DSV in the post-launch phases through deployment and commissioning prior to reactor startup.

Finally, the Mission Module was comprised of the suite of instruments and supporting elements that would be mounted to the DSV, primarily in the area of the Spacecraft Bus. The Mission Module would have been unique to each mission, but would have likely included common mounting elements including a scan platform and turntable.

5. MANAGEMENT EXPERIENCES

At its peak in Phase A, the Project had more than 500 full-time-equivalent people working on the Project. In addition, the life cycle cost estimate (including the launch vehicle) was estimated to be more than $10B. Starting from a small embryonic pre-project team in November 2002 through the completion of Phase A in October 2005, the Prometheus Project team developed several management concepts that should prove useful to future projects with similar scope and complexity. The following sections are devoted to discussing the key management experiences relevant to those projects.

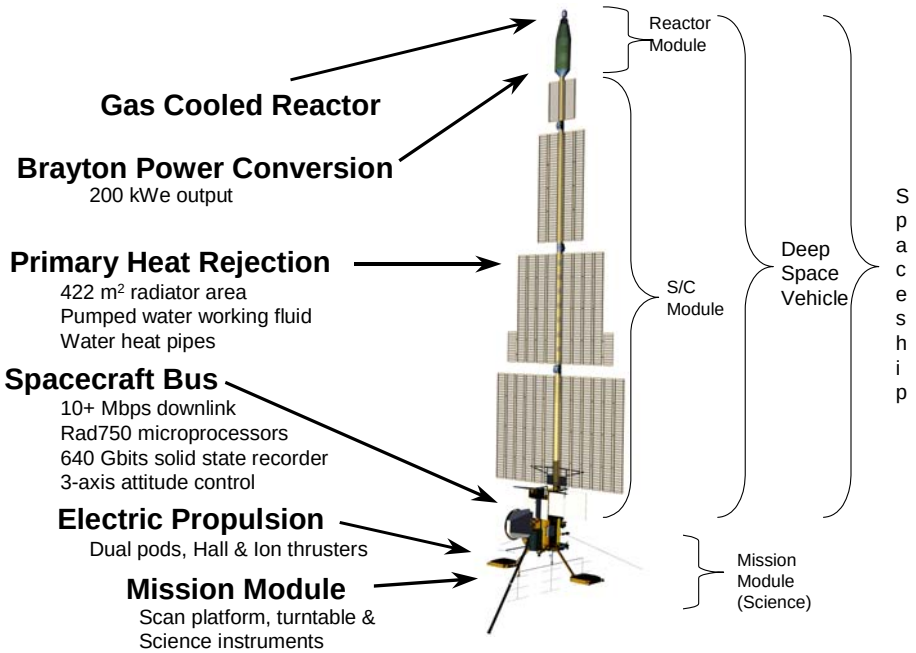

Figure 2 – Spaceship Overview.

Utilization of Technical Capabilities

From the beginning, the newly formed Project team realized that no single organization possessed all the expertise necessary to succeed in the Prometheus development effort. The technologies, developments, and experience bases for Prometheus resided at many different organizations:

(1) Reactor experience and official Federal authority resided with the DOE.

(2) Deep space mission development and execution expertise resided with JPL.

(3) Technology development exclusive of the reactor resided with NASA's Glenn Research Center (GRC), JPL and industry.

(4) Large spacecraft development and its integration resided with industry.

Therefore, the Project established a multi-organizational team that included:

(1) JPL.

(2) NRPCT, which included the Knolls Atomic Power Laboratory, Bettis Atomic Power Laboratory, Bechtel Plant Machinery, Inc., and supporting Department of Energy (DOE) laboratories, universities and industry.

(3) Five NASA Centers: Ames Research Center [ARC], GRC, Kennedy Space Center [KSC], Langley Research Center [LaRC], and Marshall Space Flight Center [MSFC]).

(4) NGST and its subcontractors.

(5) Universities and other individual partners.

The individual members of the team were separated culturally as well as geographically and used disparate processes, procedures, and tools. Technical experts from across the country were utilized to address the various challenges presented by the Project.

The technical activities were coordinated by the Chief Engineer and implemented across the Project elements by the System Managers and System Engineers.

A hierarchal structure of system engineering teams was instituted to ensure that system-level issues were driven from the top. Each system engineering team contained representatives of the involved organizations. Crosscutting system engineering teams were initiated to focus on areas with complex interfaces, such as the power plant, structures, power generation and distribution, and information systems. This structure of system engineering teams was overseen and under the overall responsibility of the Chief Engineer, though each team operated under the leadership of the organization responsible for that element of the WBS.

This use of hierarchal system engineering teams under the direction of a Chief Engineer allowed us to effectively leverage the proven technical and programmatic capabilities of each participant organization.

Overcoming Cultural and Organizational Differences

The best national capabilities were required to address the technical challenges of the Prometheus Project; this presented the team with the management challenges of:

(1) Harnessing the potential of a culturally and organizationally diverse team.

(2) Successfully operating across organizational boundaries.

The project management team established a systematic approach to dealing with this challenge. The approach cut across the Project structure and included frequent interactions and meetings at various management and technical levels of the Project, co-location of key personnel, and instilment of a sense of ownership and responsibility of all participants.

Inclusion of NASA Deputy Center Directors and other senior executives from industry in the Project Advisory Council was used to break down barriers and to establish a common understanding and a productive and trusting relationship across the Project. Also, the selection of key qualified personnel from across the participant organizations to positions of responsibility and authority (for example the Technology Manager/Deputy Spacecraft Manager was from GRC) was essential in ensuring the cohesiveness and seamless interaction of the overall team. This was very evident during the PMSR, where it was difficult for the review board members to distinguish the home organization of the presenters.

The Project comprised a number of organizations with different work cultures and organizational mapping. This initially resulted in confusion and frustration, where coordination of functions and communication were slow. However, diligent work by the team resulted in a very cohesive structure.

NASA Center representatives were co-located at JPL. The representatives were not the managers for the Project at the other Centers, but were senior-level staff. This provided real-time support to the Project during Phase A and was especially useful in preparing for PMSR. As things evolved on the Project, real-time interaction and participation with the various Centers resulted in better products based on the most current information. Project team members were more likely to solicit information from appropriate team members

from other Centers and organizations rather than make assumptions on their own.

Coordination activities, meetings, workshops, and retreats were held starting early in the project lifecycle to help describe and understand the method of doing business across the Project and its supporting organizations. Almost always, these activities included informal, social functions to help break down the cultural barriers. This action required repetition to get people to understand the different styles and processes used across the organizations. Consciously assigning tasks that required multiple organization contributions created a sense of trust. This approach also proved necessary for each organization to clearly identify their priorities to the other partners, so that everyone could see how they affected each other and support high-priority actions of the other Project partners.

Cultural similarities were also evident. Although it may have been expressed by different organizations with different terminology, there was a general attention to rigor and good project management techniques apparent from all participants. Safety was the number one priority of all project participants. Finding these and other common goals, values, and cultural similarities was a focus of the Project's early coordination activities.

Documentation of Technical Decisions

Technical decisions are made throughout a project's lifecycle and across the project disciplines. Documenting the technical basis and rationale associated with technical decisions is essential to an organization's ability to substantiate, communicate, and verify designs. The practice of making technical decisions without official documentation is all too common in the aerospace community (e.g., power point engineering). This can severely impact a project or individual's ability to reference such technical decisions and to validate or verify designs. This approach also limits the ability of a project to communicate decisions to project personnel.

The Prometheus Project instituted a requirement to document all technical decisions in an official memo or report with appropriate discipline and organizational review. This was done to ensure that the decision and supporting justifications were properly documented and made available to other personnel and used for future activities, which, for complex projects, could be many years in the future.

Establishing Team Interfaces Across the Project

The Prometheus Project's size and complexity, and the widespread geographical location of Project participants, required the implementation of efficient and effective communication and interfaces across the Project. The team addressed this challenge by providing a wide range of communication and interface methods and encouraging frequent direct interface between Project personnel.

The Project's use of video conferencing for Monthly Management Reviews (MMRs), weekly staff meetings, etc. enabled a cost-effective implementation of effective team relationships (seeing and hearing someone provides more effective communication) and provided a good way to develop team relationships without the expense of extensive travel. Having this as the standard process for staff meetings each week allowed all organizations the opportunity to work out the logistics of video conferencing. Video conferencing and other communication tools, such as web-access file sharing, were used for other meetings as well.

The Project rotated the base location of MMRs between the Project participants' home sites. This provided two benefits:

(1) Reduced travel required for non-JPL team members.

(2) All team members had the opportunity to visit others sites, meet Center/organizational management, and tour facilities.

Rotation of the MMR sites also gave team members a stronger sense of partnership and ownership.

To facilitate communication across the Project, weekly project status reports were issued to all Project personnel. Also, a quarterly newsletter was mailed to the home address of all team members. In addition, all project personnel were given access to the Project's electronic library.

The Responsibility Assignment Matrix

The large number of organizations in positions of responsibility required the Project to develop a Responsibility Assignment Matrix (RAM). The RAM delineated which organization had what responsibilities at various points of time during the Project development cycle for each item of the WBS.

Early in the Project, after the development of Technical Baseline 1, a detailed WBS was developed. This WBS was, in turn, used to develop the RAM. The Project RAM was developed down to the subsystem level of the WBS. The RAM specified for each WBS item in a time-phased manner (i. e., Phase A/B, C/D and E) the following assignments:

(1) Requirements Agent: Who is responsible for developing the requirements on a work element?

(2) Design Agent: Who is responsible for the design of the work element?

(3) Design Approval Authority: Who is responsible for approving the design for the work element?

(4) Design Concurrence Authority: Who is responsible for concurring with the design approved by the design approval authority?

(5) Integration Agent: Who is responsible for integrating a collection of work elements in the WBS?

(6) Co-location site: Where will the majority of work be performed for the work element during the different phases of the project?

Prior to the development of the RAM, there was debate and disagreement on who was in charge of different parts of the Spaceship without a clear process for resolution. In the process of developing the RAM, Project members focused on the various issues; over time, these issues were largely resolved and documented. The Project staff worked these issues directly with the various JPL technical divisions and with the different NASA Centers. The RAM development also allowed the JPL technical divisions to work with their counterparts at the other NASA Centers to help resolve issues. Once NRPCT joined the project, the RAM became an effective tool to quickly work with NRPCT to document responsibility assignments.

NASA Center Interfaces

The Prometheus Project required the use of many NASA Centers to support technology development and system implementation. This required the Project to develop a good working relationship that focused on long-term development and system implementation.

The following approach was used to establish and document NASA Center interfaces:

(1) Early in the Project, the Project staff traveled to each of the various NASA Centers to discuss possible working relationship. These meetings included, where possible, a meeting between the Center Director and the Prometheus Project Manager.

(2) Based on these meetings, if a role was identified for the Center, a Center lead was identified and the need to co-locate at least one senior person from the Center to the Project office at JPL was discussed. This co-location of Center staff proved to be very useful.

(3) A high level Memorandum of Agreement (MOA) was developed and signed off by the Center Director and the JPL Director.

(4) After the MOA was completed, a more detailed Management Plan (MP) was agreed to and signed by the Center Lead and the Prometheus Project Manager.

(5) The Project held annual budget workshops wherein the budget for the next period was agreed to by all parties, rather than working these details in an informal manner with each Center in isolation.

(6) Following the budget workshops, the funding for the needed tasks was documented by the use of web-enabled Work Agreements (WAs). The WAs were signed off between the Center Lead and the Project System Manager in charge of the particular WBS elements that contained the WA.

(7) The Project Manager convened a Project Advisory Group to advise the Project. This group included the Deputy Center Directors from each supporting organization and met on a quarterly basis.

(8) Whenever we had visitors from another Center at JPL, the Project Manager went out of his way to schedule an after-hour social gathering with these people and the Project staff.

The Project worked hard to establish strong and effective communication channels between Project participants at JPL with Center participants (including those working directly on the Project and senior executives at the participating Center). The Project also recognized the importance of establishing clear and documented work agreements and responsibilities, which helped draw on the strength and focus the participating organizations.

NRPCT Interfaces

At the request of NASA, the Secretary of Energy assigned to DOE-NR the responsibility of providing to NASA the space nuclear reactor for Prometheus. DOE-NR formed the NRPCT and assigned to them the responsibility of implementing the NR portion of the Prometheus Project. The NRPCT was brought into the Project about one year after Project start; however, the NRPCT quickly developed a highly effective team.

The interactions between JPL and NRPCT began in May of 2004 with a management meeting between NR, NRPCT and JPL. This was followed by a series of briefings to the NRPCT team as a whole, both at NRPCT and JPL. The briefings were followed by NRPCT joining the weekly Spaceship design team video-conferences. At the MMRs, the NRPCT Project Manager would almost always present the NRPCT status report in person, instead of via the videoconference method.

NR and NASA HQ, with JPL and NRPCT support, developed a Memorandum of Understanding between the two agencies that was signed by the Deputy Administrator for the DOE Office of Naval Reactors and the NASA Administrator. NR and NASA, with the support of JPL and NRPCT, also developed a more detailed Memorandum of Agreement (MOA) between the Associate Administrator of NASA ESMD and the Program Manager for Space Reactors at DOE-NR. Development of the MOA between NRPCT and JPL was underway when the Project was terminated. The Prometheus Project Manager and the NRPCT Project Manager developed a good, effective working relationship that would have gone a long way in ensuring mission success if the Project had been continued.

While integrating teams from two different agencies with very different missions was a challenge, several factors ensured the success of the relationship. Emphasis was placed on finding the similarities between the organizations, and a concerted effort was made to develop personal relationships between team members. Structured processes were used to define roles and responsibilities and govern interactions. However, the most effective factor related to the strong commitment of the team to the success of the Project.

Cost Analysis Requirements

The Prometheus Project's high visibility within NASA demanded a process that would deliver the highest quality Life Cycle Cost Estimate (LCCE) (and Independent Cost Estimates [ICEs]) possible for such an early stage in the life cycle. The Project recognized this and responded with the development of a Cost Analysis Requirements Description (CARD) document for the JIMO 2015 mission. The CARD was used as the requirements document for NASA's ICE and other ICEs developed by the Project for comparison to the Project's LCCE. These comparisons by the estimators were then used to resolve and/or understand issues related to incorrect assumptions, simple errors, misconceptions, or differences of opinions between the cost estimates related to each element of the WBS.

The process to develop the CARD began with the development of a detailed schedule with milestone dates for key activities, including a kickoff meeting, training, status meetings, and needed reviews. CARD templates were developed by the Project's Business Office in conjunction with the lead System Managers and were provided to guide the authors in the format and content required for the document. Weekly status meetings were held to ensure questions and issues were addressed by the Business Office.

The Project engaged NASA's Independent Program Assessment Office (IPAO), which has the responsibility of preparing the NASA official ICE, during the first year of the Project and well before the CARD development started. To ensure IPAO would be familiar with the complexities of Prometheus, the Project held coordination meetings and cost model demonstrations and invited the IPAO representatives to participate in Project design reviews, design team meetings, and other technical interactions.

To ensure the quality of the cost estimates, the Prometheus Project devoted significant resources and oversight to the development of the CARD. Thorough reviews by NASA, the Project, and IPAO representatives resulted in only minor differences in the ICEs and the Project's final bottoms-up cost estimate. Early participation by IPAO in Phase A also ensured an efficient and timely ICE. Participation in design reviews by IPAO gave excellent insight and allowed timely adjustments to cost models in support of the Prometheus LCCE.

Mission Assurance Team Engagement

The Project's Mission Assurance Office was staffed and organized to develop the Project requirements, support the development of the system designs, identify risk elements, and support the selection of the Spacecraft Module contractor. The organization of the Office was similar to the overall Project structure and allowed for a focus of responsibility and accountability. Mission assurance requirements were documented to support the RFP and contractor selection activity. Line and Project reviews of the requirements documents were conducted to ensure compliance with institutional standards and satisfaction of Project needs.

The Project Mission Assurance Manager had the responsibility for overall management of the mission assurance activities and for coordinating with the NRPCT and the NASA Centers on mission assurance issues; the Spacecraft Assurance Manager had similar responsibility with NGST. This allowed for a defined single point of contact and retained the contractual line of responsibility.

The unique radiation requirements for the Project, which affected materials, electronics, and technology development, required early coordination to maximize the effectiveness of the mitigation approaches. The Mission Assurance Radiation Lead was responsible for that coordination across all organizations within the Project. Early in the development, the Project realized that communication of existing knowledge was as important as obtaining new data. Therefore, an intensive radiation effects training and communication program was put in place to educate the Prometheus team. The impacts of radiation effects permeated through the system engineering aspects of the Project in areas such as reliability, fault protection, operating scenario development, and mass properties.

The Mission Assurance team was staffed to support the development of the RFP and related Mission Assurance requirements. This involvement facilitated a very structured set of requirements and allowed for the selection of discipline leads and establishment of points of contact across the project structure. This team also evaluated the resulting proposals to assess the understanding and compliance of each competing contractor to these requirements.

Early identification of driving mission assurance requirements and involvement of appropriate personnel was critical for addressing issues before they become design or cost drivers. Utilization of mission assurance personnel to develop a structured approach to requirements development and planning at the early stage in the Project was also critical for dealing with the multiple interfaces and challenging environments of the JIMO mission.

A clear understanding of the capabilities of the partner organizations and contractors and the structure of their internal workforce and responsibilities was critical to arriving at a cohesive mission assurance team. The Project management team invested an appreciable amount of time addressing this area, resulting in clear lines of responsibility and authority across organization boundaries.

Technology Development Process

Traditionally, technologies are developed by laboratory researchers, independent of project requirements, insight, or review. What technologists develop, therefore, does not always accommodate the needs of specific flight projects.

On Prometheus, we brought all of the supporting technology efforts into the Project, designated the Project Technology Manager to also serve as the Deputy Spacecraft Manager, and generated disciplined plans for the six technology areas (excluding Reactor technologies, which were handled separately by NRPCT). The Technology Manager provided the requirements for the technology development plans in a technology plan requirements document. This document outlined in detail the items that each technology plan was required to address. It specified the level of technology maturity required by the Preliminary Design Review (PDR). Subsequently, each detailed technology development plan defined the technology's specific criteria for the level of maturity at the PDR milestone, identified verifiable demonstration milestones, provided a fallback plan, and established an independent technical peer review board.

The technology teams were led by government personnel. Five of the six teams had members from at least 2 different NASA Centers; each team also included industry and university participation. These teams operated under the overall leadership of the Technology Manager, who also controlled the funding of these teams.

Project Safety

Because of the large number of participants in the Project, and the use of a nuclear system, the Project Office included a Safety Manager. The Safety Manager was independent of the Mission Assurance office. The Safety Manager was responsible for personnel safety, facility safety, and hardware safety.

Many organizations had safety regulatory authority over the Prometheus Project. DOE-NR was legally responsible for the safe and secure use of the nuclear system, and would always maintain ownership of the reactor. NR would also define the nuclear safety and security regulations for the nuclear operations that would be required at KSC and the Cape Canaveral Air Forces Station (CCAFS). In addition, KSC/CCAFS had local regulations based on Federal requirements, which also had to be met. Each organization that performed Project work was accountable for complying with the applicable Federal, State, and Local regulations, and the formal safety requirements of their organization.

No set of regulations overrode any others. The Project was required to meet all safety and security regulations. When several regulations and organizations were to operate in a given facility, the full set of regulations and requirements were to be evaluated and integrated, so that the workforce was clear on what rules were to be followed.

To provide this integration, early in Phase A, meetings were necessary between all of the participant safety leads. In any project of this magnitude, especially one with an unusual potential hazard, clear integration of safety and security regulations is necessary to prevent confusion on the part of the workforce over which rules apply. Workers and public health and safety, and the protection of high value hardware and facilities, must be of highest priority of the Project.

6. RECOMMENDATIONS

The Prometheus Project was a complex undertaking, both from a technical and management standpoint. The management team developed several management approaches, as documented in this paper, that should prove useful for projects of similar scope and complexity.

The authors recommend that projects of the scope of Prometheus that require the involvement of many different organizations establish strong working relationships with the participant organizations and involve the Center management throughout the process. The project must understand the capabilities of the partner organizations and contractors and structure their internal workforce and responsibilities accordingly. This can be facilitated by developing clear and documented responsibilities for each organizations and documenting this in a Responsibility Assignment Matrix. This allows team members to focus on the issues and reduces the inherent and reoccurring conflicts associated with deciding on who is responsible for each element of the WBS. The role and organization of the mission assurance team should be addressed early in the project lifecycle.

Future projects should establish a rigorous process to document technical decisions, with supporting information and a defined process for review and approval. Presentations should only be used as supporting material to help in the communication process.

It is recommended that a project office commit to a technical design "freeze" for costing purposes early enough to allow adequate time to develop a thorough CARD and cost estimates.

Projects with high technology content should ensure that the technology developments needed by the project are controlled by the project and funded by the project, and that detailed technology development plans are developed and implemented.

Though these approaches were developed for a project with a geographically and culturally diverse team, many of these approaches can and should be implemented in modified formats for smaller, less complex projects.

REFERENCE

Prometheus Project Final Report, JPL document 982-R120461, October 1, 2005.

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