Systems Engineering Approach Used in the Development of the MESSENGER Propulsion System

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The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission is the seventh in the series of NASA's Discovery missions. The MESSENGER spacecraft was launched 3 August 2004 and is currently on its trajectory to Mercury. It will spend nearly 7 years en route to the planet. During that time, the spacecraft propulsion system will provide periodic attitude control operations and ΔV burns as commanded by the MESSENGER mission operations team. Upon arrival, the propulsion system will perform an orbit insertion burn and the spacecraft will orbit the planet for one Earth year gathering scientific data. The MESSENGER mission required a low-mass propulsion system capable of delivering approximately 2300 m/s of ΔV that could be provided to The Johns Hopkins University Applied Physics Lab (JHU/APL) in time to meet the launch-date-driven spacecraft integration schedule. Early concept design trades selected a propulsion system that was highly integrated with the spacecraft, used off-the-shelf qualified system components to the greatest extent possible, and included a new mission-specific propellant tank design. To meet the technical and schedule requirements, the MESSENGER propulsion system team used a highly disciplined systems engineering approach founded on an early understanding of the constraints associated with the entire mission. The mission phases evaluated included propulsion system development and test, spacecraft integration and test, launch on a Delta-II heavy launch vehicle, and in-flight operations. This paper describes how the early implementation of systems engineering disciplines resulted in a propulsion system that successfully integrated with the spacecraft, withstood the severe launch environments, provided nutation control during the launch vehicle's third stage burn, and has completed nearly 2 years of flight operations to date.

Nomenclature

AFT = *Auxiliary Fuel Tank*
AT = *Acceptance Test*
ATP = *Authority to Proceed*
CDR = *Critical Design Review*
DAR = *Design Assurance Review*
DPS = *Deorbit Propulsion Stage*
EIDP = *End Item Data Package*
JHU/APL = *The Johns Hopkins University Applied Physics Laboratory*
JPL = *Jet Propulsion Laboratory*
LETS = *Liquid Engine Transient Simulation*
LVA = *Large Velocity Adjustment*
MESSENGER = *MErcury Surface, Space ENvironment, GEochemistry, and Ranging*
MPS = *MESSENGER Propulsion System*
MPT = *Main Propellant Tank*
MR = *Mixture Ratio*
NEAR = *Near Earth Asteroid Rendezvous*
NTO = *Nitrogen Tetroxide*
PDR = *Preliminary Design Review*
PF = *Protoflight*
PFT = *Primary Fuel Tank*
POD = *Point-of-Departure*
QT = *Qualification Test*
RFQ = *Request for Quote*
SE = *Systems Engineering*
SLED = *Structural Loads and Environments Document*
SOW = *Statement of Work*
SRR/CoDR = *Systems Requirements Review/Concept Design Review*
TIM = *Technical Interchange Meeting*
TRD = *Technical Requirements Database*
TVC = *Thrust Vector Control*

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NASA = *National Aeronautics and Space Administration* *TRD* = *Technical Requirements Database*

I. Introduction

Design and development of any system driven by schedule constraints can be fraught with inefficiencies in program execution and risk management, resulting in cost growth, schedule slips, and—in the worst case—the inability to meet program requirements. Lack of focus is often attributed to inadequate technical requirement definition and verification planning. To avoid this, the MESSENGER Propulsion System (MPS) team began the system development process with a small but experienced group focused on early establishment of requirements and verification strategies to prepare for program execution as well as early initiation of key risk-reduction activities to allow time to address any deficiencies. This early focus on understanding and documenting these programmatic fundamentals provided the foundation from which the system was developed. The fully compliant system was delivered to The Johns Hopkins University Applied Physics Laboratory (JHU/APL) to support the launch-date-driven schedule.

The discussion begins with a brief description of the mission and delivered MPS. The remainder of the paper describes the systems engineering (SE) process used to develop the point-of-departure (POD) design into the system currently propelling the spacecraft on its path to Mercury.

II. The Mission

NASA's Jet Propulsion Lab (JPL) and JHU/APL's mission design team developed an innovative approach to trajectory design from which the MESSENGER mission design was formulated. The mission included a launch on a Delta IIH launch vehicle followed by a spacecraft route designed to minimize propellant consumption through use of planetary "reverse gravity assists." The required propellant usage was significantly reduced by using the gravitational pull of planets to slow the spacecraft. Fig. 1 shows the baseline trajectory and planetary fly-by points. April 2004 was selected as the most favorable launch window with an August 2004 window as the backup since the mission was dependent on the specific alignment and timing of Earth, Venus, and Mercury to lower the propulsion requirements. The early mission designs required a high but achievable ΔV of 2700 m/s that was later reduced to 2300 m/s through additional refinement of the mission trajectory. Achievement of the mission design required realization of a lightweight spacecraft with a high wet-to-dry mass ratio. The final fully loaded 599.4-kg MPS was 54 percent of the total spacecraft launch mass.

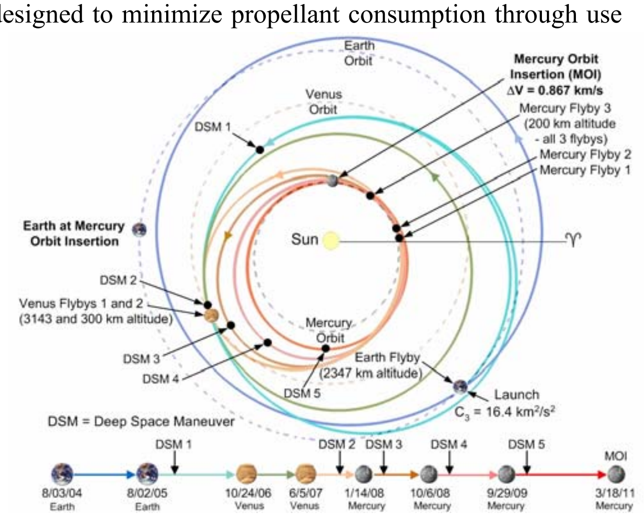

Figure 1. Mission profile.

III. System Description

The delivered MPS is a pressurized bipropellant, dual-mode system using hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4 or NTO) in the bipropellant mode and N_2H_4 in the monopropellant mode. The system is shown in layout and schematic form in Fig. 2. The MPS hydraulic schematic consists of four main subsystems; pressurization, fuel feed, oxidizer feed, and thruster module. Additional MPS elements include the secondary structures, electrical subsystem, and thermal management subsystem. Total propulsion subsystem dry mass was 81.74 kg.

Propellant storage is provided by three main propellant tanks (MPTs), with two used for fuel and one for oxidizer storage, and a refillable auxiliary fuel tank (AFT). Pressurant storage is provided by a dual-outlet-port helium pressurant tank. All MPS tanks were provided by ATK Space Systems, Inc. The MPTs (ATK PN 80433-1) were designed, fabricated, and qualified for MESSENGER. The AFT (ATK PN 80444-1) and pressurant tanks (ATK PN 80445-1) were "off-the-shelf" with minor interface configuration changes. At launch, the AFT contained 9.34 kg of N_2H_4, and each main fuel tank contained 178.0 kg of N_2H_4, respectively, while the oxidizer tank contained 231.6 kg of N_2O_4. The helium tank contained 2.45 kg of helium at a launch pressure of 3,375 psia.

The MPS includes a total of 17 thrusters. Three thruster types, arranged in five different thruster module configurations, provide the required spacecraft forces as illustrated in Fig. 3. The Large Velocity Adjustment (LVA) thruster is a flight-proven, Leros-1b provided by Ampac-ISP. The LVA operates at a nominal mixture ratio (MR) of 0.85, provides a minimum 667.0-N of thrust, and operates at a specific impulse of 316 s. Four 22.0-N monopropellant LVA thrust vector control (TVC) thrusters (also identified as C-thrusters) provide thrust vector steering forces during LVA thruster burns and primary propulsion for most of the smaller ΔV maneuvers. The LVA TVC thrusters are flight-proven Aerojet P/N MR-106Es that have a specific impulse of 234 s. They are fed with N_2H_4 in both the pressurized and blow-down modes. Twelve monopropellant thrusters provide 4.4-N of thrust at a specific impulse of 227 s for fine attitude control burns, small ΔV burns, and momentum management. The 4.4-N thrusters are flight-proven Aerojet P/N MR-111Cs. These thrusters are also fed with N_2H_4 in both the pressurized and blow-down modes. Eight 4.4-N thrusters (A and B) are arranged in double canted sets of four for redundant three-axis attitude control. Two 4.4-N thrusters (S) are used to provide velocity changes in the sunward direction. The final two 4.4-N thrusters (P) are used to provide velocity changes in the anti-sun direction. The P thrusters are located on the spacecraft -Y side and protrude through the spacecraft sunshade. The P and S thrusters point along the spacecraft +Y and -Y axes to provide ΔV thrust in a different direction from the C thrusters and LVA.

Integrating hardware includes service valves, filters, latch valves, regulators, check valves, and pyrotechnic isolation valves.

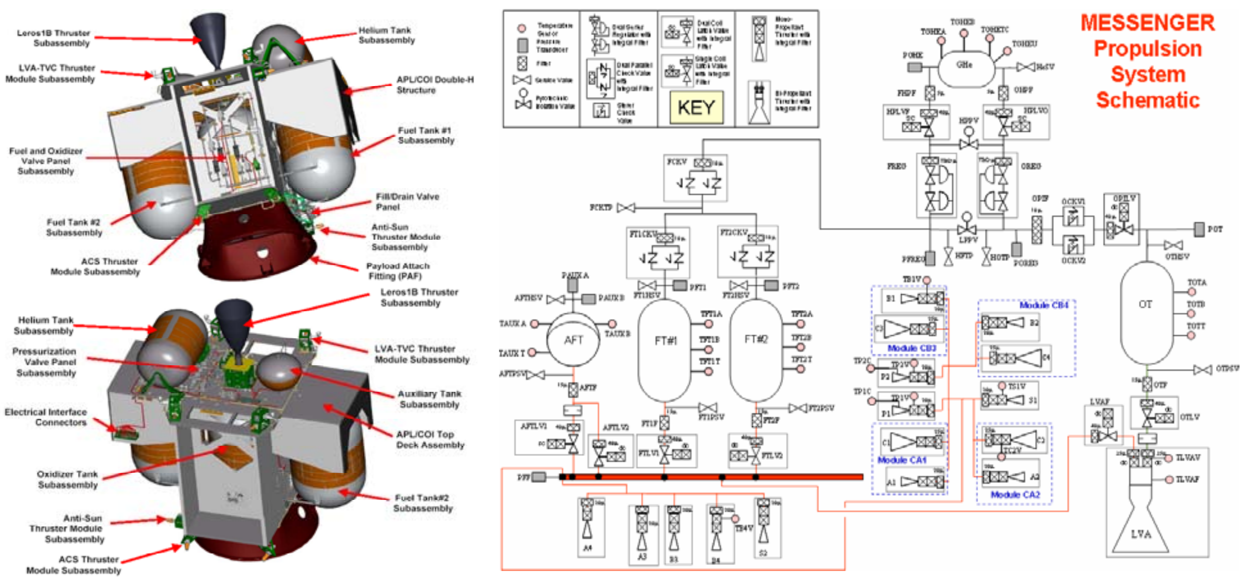

Figure 2. System layout and schematic.

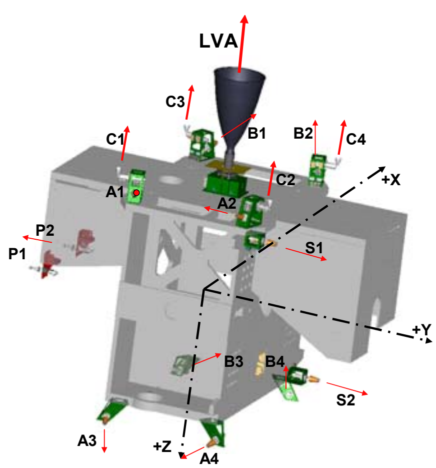

Figure 3. MPS thruster arrangement.

IV. Point-of-Departure (POD) Design

Reference 1 discusses the development of the POD design that, in addition to the mission design, served as input into the SE activities that are the subject of this paper. The key to achieving a lightweight spacecraft was recognized early in the conceptual design phase and based on using a dual-mode bipropellant propulsion system directly integrated with the spacecraft structure. The propulsion suite selected for the POD design minimized the necessary propellant load through use of a single high-performing thruster for large ΔV maneuvers and monopropellant thrusters for propellant settling, momentum management, and attitude control. An integral propulsion system/structure was selected to reduce system mass further through direct mounting of propulsion system components to the structure, thus reducing the need for secondary structure. A three-equal-volume tank concept with each tank side-mounted to the spacecraft structure center box was adopted for two main reasons. This approach allowed load transfer through the side panels, into the spacecraft square-to-round adapter, and to the Delta II interface ring, resulting in an acceptable load distribution at the Delta II interface ring. This POD design also had the advantage of using predominantly off-the-shelf hardware—an important consideration in a schedule-driven program. The MPT was the only new component design. The design had to satisfy the propellant storage, low mass, and envelope requirements associated with the mission and POD design. The POD design illustrating the spacecraft structure, propellant and pressurant tank packaging, and location of the high-performing LVA thruster is shown in Fig. 4.

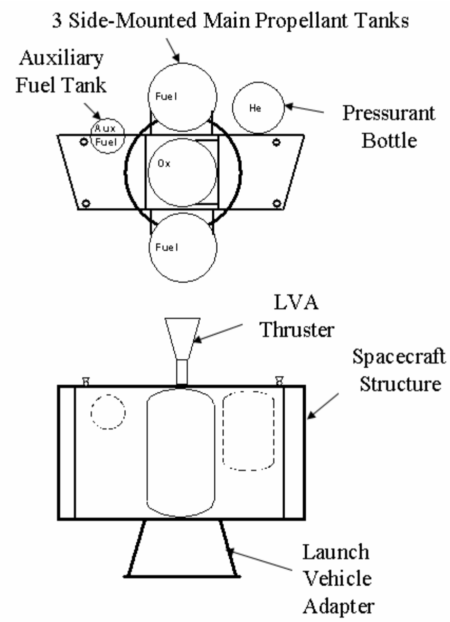

Figure 4. POD design.

V. The Systems Engineering Process

A. Establishing Requirements, Scope, and the Baseline Propulsion System Concept

At the formal start of the propulsion system development activity, the baseline mission profile, POD design, and baseline program scope were established. Once authority to proceed (ATP) was given, a small team comprising engineering and program management personnel along with support staff from Aerojet's Materiel group set forth to further detail the path leading to product certification, system delivery, successful launch, and in-flight operations.

Aerojet was tasked with establishing the propulsion system specification that reflected the performance and packaging requirements of the mission profile and POD design as well as statement of work (SOW) that reflected the required scope of the contract. The importance of establishing well-thought-out requirements was understood by Aerojet and JHU/APL since implementation of their content affected the efficiency and effectiveness of the entire development activity from concept selection through product certification. The specification and SOW were levied on Aerojet as contractual documents upon completion of the documents and approval by JHU/APL.

Figure 5 describes the SE process used from ATP through the MPS Systems Requirements Review/Concept Design Review (SRR/CoDR) that established the information suite upon which the execution phase of the program was based. The first three steps focused on establishing the MPS specification. Three interdependent tasks focusing on MPS concept definition, program risk reduction, and verification planning were performed in parallel. The program scope was updated and the requirements management tool was established. Finally, the content of the future certification report was defined.

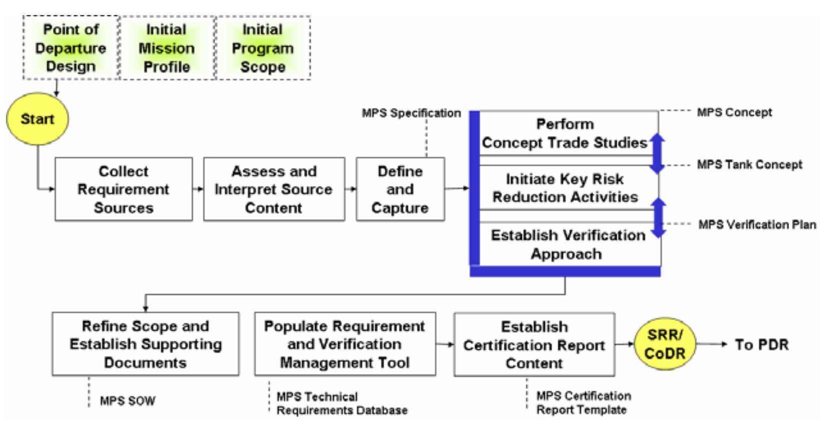

Figure 5. SE Process—ATP to SRR/CoDR.

1. Collect

The "collect" step entailed identifying all potential requirement sources. These included the previously mentioned POD design and mission profile as well as those sources that would provide the basis for "constraint" requirements. These included EWR 127-1, Boeing payload requirements, and initial versions of JHU/APL's product assurance, component environments and verification, and contamination control documents. Technical interchange meetings (TIMs) between JHU/APL and Aerojet also surfaced requirements. Aerojet safety requirements were identified as well since the system would be fabricated and tested on the Aerojet facility. Fig. 6 depicts the information set that formed the basis of the propulsion system specification.

2. Assess

The "assess" phase required a thorough evaluation of the content of each source document to distill the information into a concise set of propulsion system requirements. Product knowledge, system development, and mission operation experience gained on the development of the Near Earth Asteroid Rendezvous (NEAR) and NASA's X-38 Deorbit Propulsion Stage (DPS) programs were invaluable in determining the applicability and significance of potential requirements.

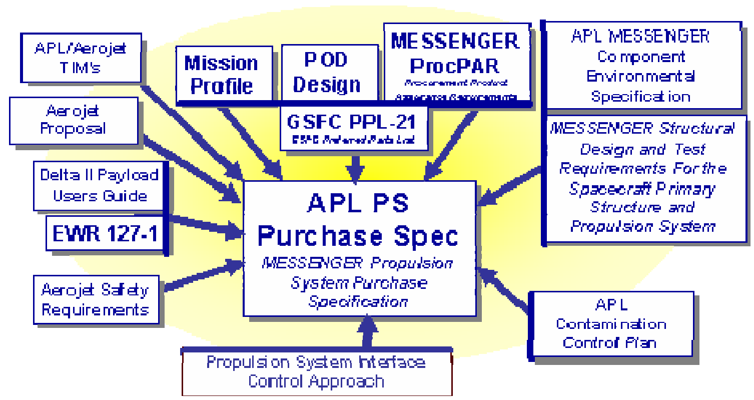

Figure 6. Source documents were collected.

The "assess" phase also provided the opportunity to consider thoughtfully the design implications tied to the requirements. For example, while the innovative mission profile reduced the total ΔV requirements, it also increased total flight time and necessitated use of the LVA thruster a minimum of six times throughout the mission. The LVA thruster had to provide the ΔV for course corrections en route to Mercury, orbit insertion, and post-insertion orbit adjustments. For a dual-mode propulsion system, the repeated LVA operation directly affected the propulsion system fuel and oxidizer pressurization system and its ability to limit the diffusion of NTO. NTO diffusion is a failure-related design consideration for long-duration missions. NTO vapor migration results in NTO accumulation in the fuel pressurization system and could result in energetic reaction and hardware failure. Selection of the MPS configuration had to consider this potential occurrence.

The requirement combination of low spacecraft mass, high wet-to-dry mass ratio, location of the propellant tanks in the POD design, and the launch on a Delta IIH surfaced another key design consideration. Since the Delta IIH third stage is spin stabilized, the associated propellant movement within the propulsion system tanks could cause the entire spacecraft/third stage stack to "wobble" or nutate. Although the Delta IIH third stage includes an on-board thruster system designed to compensate for payload nutation, its ability to adjust the nutation level of the stack is limited. Therefore, the MPS design had to provide adequate control of propellant movement to remain within the compensating capability of the Delta IIH third stage.

The planned spacecraft test approach surfaced another design consideration. The test approach included a spacecraft-level protoflight sine vibration test. A minimum fundamental frequency goal of 85 Hz was levied as a design goal for the propellant tanks to allow decoupling of the tank and spacecraft structure primary modes during this test.

3. Define and Capture

The "define and capture" phase focused on establishing the requirements that governed the propulsion system design and articulating them in written form. Functional and performance requirements were determined based on the operational capability and mission duration defined in the mission profile. Top-level functional requirements emphasized that the MPS must provide the impulse for propellant settling, large ΔV maneuvers, small maneuvering control, unloading of the spacecraft reaction wheels, and attitude control as well as all propellant and pressurant necessary to enable these functions. Performance requirements defined how the system would be judged in its ability to meet these functions. Quantified values for requirements such as system weight, static and dynamic center of gravity, thruster performance and life, propellant and pressurant storage volumes, useable propellant, quality of propellant, power usage limits, and thermal control ranges were established.

Physical and constraint requirements were also determined. Physical requirements were driven by the POD design and highly integrated nature of the spacecraft structure and propulsion system. Constraint requirements associated with the suite of requirement sources were defined. The most significant design considerations were those associated with launch survival, propellant management, and limiting NTO diffusion to acceptable levels.

The final step was to "capture" these requirements. The requirements were sorted into logical groupings around which the propulsion system specification was organized.

4. Establish Concept

The "establish concept" phase began once the key requirements were defined. Trade studies to establish the baseline propulsion system schematic were performed and are discussed in more detail in Reference 1. The primary trades were focused on selection of the pressurization system design, the LVA thruster, and the propellant management approach. The figures of merit for the pressurization system trade were based on mass, cost, reliability, resistance to NTO migration, operational flexibility, packaging, and the ability to "test-as-you-fly." Thrust, specific impulse, total impulse, and operational robustness were identified as the figures of merit for the LVA thruster trades. Passive-versus-active propellant management concepts were traded based on cost, packaging, and the ability to provide bubble-free propellant immediately in event of a mission anomaly.

Figure 7 shows the baseline propulsion system design selected. Although the pressurization system selected scored midrange among the alternatives in terms of cost and mass, it scored well when the other figures of merit were considered. The dual outlet port pressurant tank configuration combined with multiple flow barriers provided by system valves provided sufficient NTO diffusion control and could be tested in the flight condition. Using pyrotechnic isolation valves both upstream and downstream of the pressure regulator provided cross-strapping capability that provided both operational flexibility and improved reliability. Finally, limiting helium storage to a single tank was attractive from a packaging standpoint. Combining a positive expulsion fuel tank with operation of settling thrusters was the selected propellant management approach, and ensuring that the tank had sufficient volume addressed the operational anomaly concern. Finally, the Leros-1b thruster was selected based on its thrust performance and operational robustness.

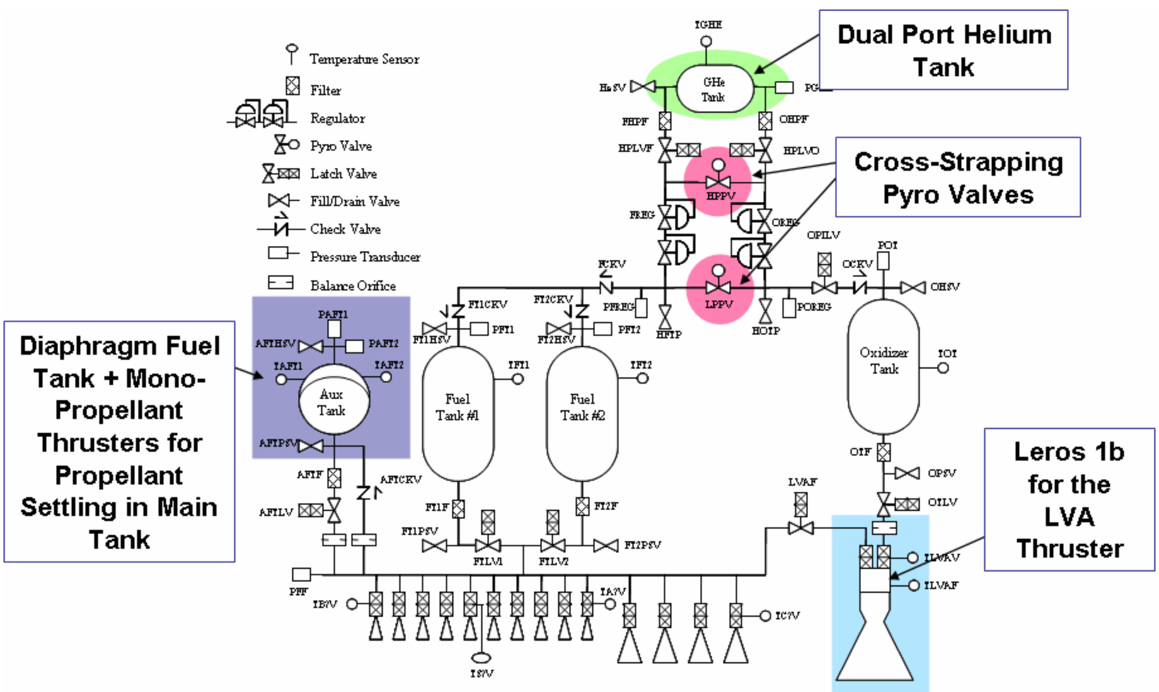

Figure 7. Baseline concept.

5. Establish the Overall Verification Plan

Prior to assigning verification methods to each requirement, the team established an overall test, analysis, and inspection approach that guided the future assignment of methods.

Test Planning

The guiding test verification document was JHU/APL's component environmental specification. This document not only identified the structural criteria and environmental load requirements but also displayed the test verification approach from the spacecraft to the major component level. Qualification tests (QTs) for new designs such as the MPT and protoflight (PF) tests for flight hardware were planned in addition to typical acceptance tests used to surface workmanship problems.

The original spacecraft level tests included PF sine vibration, acoustic, thermal bake-out, and thermal vacuum tests. As discussed later in Section 9 of this paper, the spacecraft level PF sine vibration test was discarded based on results from early MPT mounting trades and replaced with a component-level test approach. Table I describes the resulting MPS component and subsystem design verification test approach presented at the SRR/CoDR.

The specific acceptance tests for each MPS component were also established. Table II shows the matrix for the MPS integrating components. Identified system-level acceptance tests included proof, leak, and hydraulic flow using the MPS minus the thruster suite (thruster representation provided by facility valves) to verify system performance and LVA thruster inlet conditions.

Analysis Planning

Analysis plans were established to focus on gaining an early understanding of the system characteristics, developing models for mission simulations, establishing operational requirements, defining design configurations and establishing an analytical verification roadmap.

The plans are summarized in Table III.

The system fluid dynamics analysis objectives focused on understanding fluid behavior in the MPTs. These objectives included assessing tank nutation during launch and propellant slosh characteristics during the MPS operations. They also included establishing slosh models to be used by APL in mission simulations and a vortex suppression design at the tank outlet to ensure full propellant flow. An additional objective was establishing propellant settling times based on available thrust from the settling thrusters.

Table I. Planned verification test matrix—SRR/CoDR.

Component		Proof Pressure	Leak	Burst Pressure	Pressure Cycle	Sine Vibration			Random Vibration		Acoustic/ Thermal Bakeout / Thermal Vacuum
		AT	AT	QT	QT	QT	PF	AT	QT	AT	
LVA Thruster		X	X					X		X	
Mono-Prop Thruster		X	X							X	
Helium Tank		X	X								
Primary Propellant Tanks	Qual Tank	X	X	X	X	X			X		
	Flight Tanks	X	X				X				
Auxiliary Fuel Tank		X	X								
Service Valves		X	X								
Latch Valves		X	X							X	
Filters		X	X								
Pressure Transducers		X	X							X	
Check Valves		X	X								
Regulators		X	X							X	
Pyro Valve		X	X								
LVA Thruster Heat Shield								X		X	
Secondary Structure							X				
Fasteners											
Electrical Subsystem											
Thermal Management System											
Thruster Module Assembly		X	X								
Lines/Manifolds		X	X								
Hydraulic Assembly		X	X								
Top Level Assembly		X	X				X				X

AT = Acceptance Test - Performed on All Units
QT = Qualification Test - Performed on Qualification Units Only
PF = Proto-Flight Test - Performed on All Units

Table II. Planned acceptance test matrix for integration components—SRR/CoDR.

Component	Lot ATP	X-Ray	Proof Test	Dye Pen	Leak Testing	Random Vibration	Mech./ Hyd. Function	Elect. Function	Cleaning	Electrical Burn In
High Presssure Helium Filters		X	X	X	X		X		X	
Pyro Valves	X	X	X	X	X	X	X		X	
Latch Valves		X	X	X	X	X	X	X	X	
Regulators		X	X	X	X	X	X		X	
Pressure Transducers		X	X	X	X	X		X	X	X
Check Valves		X	X	X	X	X	X		X	
Filters		X	X	X	X		X		X	
Fill and Drain Valves		X	X	X	X		X		X	
Thermal Switches					X			X		X
Heaters								X		X

The system performance analysis was directed at predicting system characteristics such as manifold priming and transient flow, or “water hammer,” as well as establishing system operational requirements, such as valve sequencing and auxiliary tank refill time, using the Liquid Engine Transient Simulation (LETS) software tool. The LETS code is an Aerojet-developed software tool used to model transient and steady-state systems using the method of characteristics to solve fluid dynamic computation problems.

The Structural Loads and Environments Document (SLED) established the roadmap for structural verification. The SLED documented the structural criteria to be used in margin-of-safety evaluation, identified the loads and environments, and established how the loads were to be combined when performing the structural evaluation of the system and its elements. Table IV summarizes the structural analysis approach for the propulsion system.

Since APL was responsible for the overall thermal design, the MPS thermal analysis plan concentrated on establishing thruster post-firing thermal soak back characteristics and the LVA thruster heat shield configuration.

Table III. System-level analysis plans.

Analysis Plan	Key Analysis Objectives
System Fluid Dynamics Analysis	· Predict Nutation Time Constants
	· Determine Slosh Characteristics During PS Operation
	· Provide Propellant Slosh Model for Mission Operations
	· Establish Propellant Settling Duration
	· Define Necessary Tank Outlet Configuration for Vortex Suppression
System Performance Modeling	· Determine System Venting Requirements Prior to First Thruster Operation
	· Establish System Priming Time
	· Define System Flow Characteristics
	· Assess System Response to Single and Multiple Thruster Firings
	· Verify Acceptable System Water Hammer Pressures
	· Establish System Balance Points and Verify Mixture Ratio Control of LVA
	· Establish and Verify Auxiliary Tank Refill Sequence
Thruster Module Level Thermal Analysis	· Verify Thruster Temperatures During and After Operation
	· Establish Need for Thermal Isolation/Heat Spreader
	· Trade LVA Thruster Heat Shield Configurations
Structural Analysis	· Identify All Structural Criteria, Loads and Environments
	· Identify What Components Must be Designed for Stiffness
	· Identify What Loads Are Considered For Analysis of Each PS Element
	· Identify What Loads Are Subsequently Verified by Test

Table IV. System-level analysis approach.

System Element	Internal Pressure Loads	Structural Load Factors	Centrifugal Acceleration	Pressure Rate Change Load	Combining Loads	Sine Vibration	Random Vibration	Transportation Vibration	Acoustic
LVA Thruster	X						X (QBS)		
Mono-Prop Thruster	X						X (QBS)		
Helium Tank	X	X	X	X	X	X	X (SL)	X (SL)	
Primary Propellant Tanks	X	X	X	X	X	X	X (SL)	X (SL)	
Auxiliary Fuel Tank	X	X	X	X	X	X	X (SL)	X (SL)	
Service Valves	X						X (QBS)		
Latch Valves	X						X or X (QBS)		
Filters	X						X (QBS)		
Pressure Transducers	X						X (QBS)		
Check Valves	X						X (QBS)		
Regulators	X						X (QBS)		
Pyro Valve	X						X (QBS)		
Secondary Structure		X				X			
LVA Thruster Heat Shield						X			
Fasteners		X				X			
Electrical Subsystem									
TMS									
Manifolds/Lines	X					X			

X = Evaluation of Load Required for System Element
X (QBS) = Permissible to Qualify by Similarity
X (SL) = Include Load Case in Safe Life Analysis

Inspection Planning

The inspection plan was straightforward. The inspection method included inspection of physical characteristics of hardware as well as inspection of design disclosure documentation.

Verification Method Assignment

The verification method for each requirement was assigned to reflect the test, analysis, and inspection plans.

6. *Refine Scope and Establish Supporting Documents*

The process portions from requirement collection to verification planning were useful in refining the scope on which the propulsion system proposal was based. In addition to refining the hardware items and necessary program office, engineering, manufacturing, and quality support, it also helped define a more comprehensive set of data deliverables. Data deliverables were determined based on providing not only the documentation required to support ground processing and mission operations but also the documents intended to contain the requirement compliance assessments. Table V identifies some of the key technical data deliverables.

7. *Populate Requirement and Verification Management Tool*

Microsoft EXCEL was used to manage the propulsion system requirements and verification activities. While it initially contained only the requirements within the propulsion system specification, it was also designed to capture all future lower-level requirements. The Technical Requirements Database (TRD) format associated the selected attributes with each requirement and allowed filtering of information. Table VI illustrates the format in which this information was captured. The first attributes included were verification method and planned compliance document.

8. *Plan for Product Certification*

Table V. Key data deliverables.

Document Type	Document Subject
Analysis Reports	Propellant Slosh
	System Performance
	Mass Properties/Center of Gravity
	Structural/Dynamics Analysis
	Tank Safe Life
	Power Usage
	Materials
	LVA Heat Shield Thermal
	Thruster Plume Characteristics
	Auxiliary Tank Refill Analysis
Test Plans and Reports	Propellant Tank Qual
	Hydraulic Balance
	Proto-Flight Vibration
	Acceptance Test Summary
Mission Support Documents	Operational Sequence Document
	Autonomy Rule Analysis
	Missile System Prelaunch Safety Package
Certification Documents	Propulsion System End Item Data Package & Certification Report

Table VI. TRD format.

									Verification Method						
Specification Paragraph Number							Requirement	Value	NA	QT	PQ	AT	A	I	S	Planned Compliance Document
3	2	2					Spacecraft Coordinate System	Locations of all propulsion system elements shall be in accordance with the spacecraft coordinate system shown in Figure 3.2.2-1.						I		Engineering Drawings

The plan for product certification was also developed prior to SRR/CoDR. The TRD would be used throughout the development activity to capture requirements and verification methods prior to detailed design and provide verification and compliance information at completion of the design, fabrication, and test activities. Attributes including compliance assessment, compliance summary, and compliance document information would be added to the TRD to capture verification information. Table VII illustrates the information suite that formed the key verification elements of the certification report and describes the type of information that would accompany each attribute.

Table VII. Planned certification report content.

			Verification Method								Planned Certification Report Content			
Specification Paragraph Number	Requirement	Value	NA	QT	PQ	AT	A	I	S	Planned Compliance Document	Compliance Assessment	Compliance Summary	Final Verification Document	Location in Document
3 2 2	Spacecraft Coordinate System	Locations of all propulsion system elements shall be in accordance with the spacecraft coordinate system shown in Figure 3.2.2-1.						I		Engineering Drawings	An assessment of compliance. Typically identified as Pending, Accept, or Accept with Deviation	Brief Description of Requirement Compliance	Reference Number and Title of the Final Compliance Document	Section of the Final Compliance Document that Reader Can Go to To Get Additional Verification Detail

9. Initiate Key Risk Reduction Activities

The early risk reduction activities focused on design of the MPTs. Mission and schedule requirements were distilled into a set of preliminary requirements, Table VIII, which allowed tank development to begin prior to SRR/CoDR. Tank volume was driven by the mission requirements, use of existing tooling addressed schedule concerns, and side-mounting of the tank to the structure to eliminate load sharing came from the POD design. The design also had to meet Boeing nutation control requirements and comply with range safety requirements identified in EWR 127-1. Finally, the desire to perform spacecraft-level sine vibration testing meant that the tank had to have a fundamental frequency that was sufficiently higher than that of the spacecraft structure.

Table VIII. Preliminary tank requirements.

Requirement	Value	Requirement Basis
Tank Volume	200 Liters (12,200 in3)	Mission Delta V
Tooling	Existing	Schedule
Mounting	Side	POD
Tank Structural Load Sharing	None	Separate Structure and Tank Development
Nutation Control Features	Delta II Users Manual	Selected Launch Vehicle
Tank Design	EWR 127-1, Oct 1997	Selected Launch Local
Fundamental Frequency	< 85 Hz	Baseline Spacecraft Verification Test Approach

Early initiation of the tank development activity that was based on well-thought-out requirements proved to be highly beneficial with respect to control of cost and schedule. The activity surfaced two significant but solvable findings, and the program approach and schedule were adjusted early in the program to accommodate them.

Finding 1: Adjustment to the overall verification test approach was required

Fifty side-mounted tank concepts were evaluated using simplified finite element models to assess tank mass and fundamental frequency trends. The minimum fundamental frequency requirement of 85 Hz was found to be unachievable without transmitting structure loads to the tank. The tank concept selected had an estimated 50 Hz fundamental frequency and a calculated mass of 9.5 kg (20.9 lb).

Since the need to separate the tank design from the structure design was considered more valuable than performing final verification testing at the spacecraft level, APL adjusted the overall test approach so that protoflight sine vibration testing was performed at component levels. The final sine test at the spacecraft level was modified to a low-level sine survey used as a workmanship screen only. Since the overall verification approach was only in the planning stage, this modification was made with negligible cost and schedule impact. The minimum allowable fundamental frequency requirement was also modified to be within the design's capability.

Finding 2: Tank development must be halted until nutation control features are established

Fluid behavior analyses based on the fluid behavior analysis plan was conducted in parallel to the tank concept study. Analytically based nutation control assessments were made using the preliminary tank configuration and propellant load. The 559-mm (22-in.) diameter, 200-liter (12200-in^3) tank was required to be compliant with the Delta II nutation requirements at the planned propellant load range. Nutation is caused by the presence of energy sinks in a stack spinning about its minor moment of inertia. Propellant movement in the MESSENGER tanks creates energy sinks, and the Delta II third stage/MESSENGER spacecraft stack spins about its minor moment of inertia. The study concluded that integral nutation control features (baffles) were likely required, and subscale drop tests should be performed to determine the baffle configuration based on empirical data. The tank development activity was put on hold since the tank design could not proceed without having the nutation control baffle configuration defined. Focus shifted to determining the necessary baffle configuration.

10. Status at System Requirements Review

By SRR/CoDR, a clear set of technical and verification requirements was established, the content of the certification report was defined, the optimum system concept was selected, the key risk items were identified and in work, and required adjustments to the verification approach at both the spacecraft and propulsion system levels had been made. This became the foundation for the SE activities from SRR/CoDR through preliminary design review (PDR).

B. SRR/CoDR to PDR SE Activities

Figure 8 summarizes the SE process between SRR/CoDR and PDR. The SE activity focused on establishing lower level requirements, defining the MPT internal features required for nutation control, preparing for component selection, and updating verification plans.

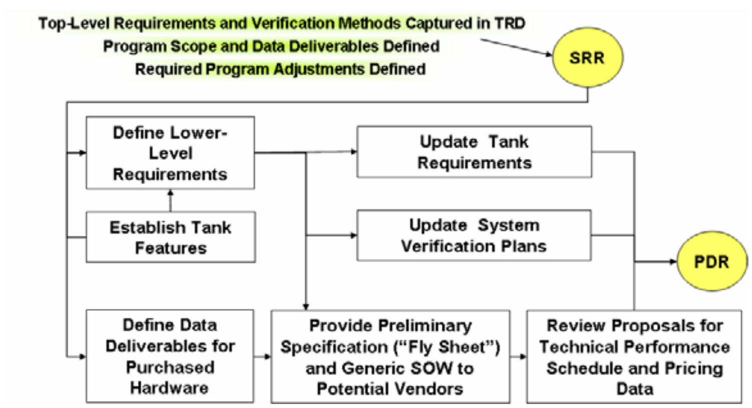

Figure 8. SE process summary—SRR/CoDR to PDR.

11. Establishing Lower Level Requirements

The propulsion system specification requirements were translated into lower-level system, subsystem, and component requirements and captured in the TRD in preparation for the component bid process and system detailed design. Analysis of system-level requirements separated the lower-level requirements into three categories. *Lowdown* requirements were directly imposed on each element. *Allocated* requirements were based on the system-level requirement parsed into each system element's apportioned value. *Derived* requirements were defined by analyzing system-level requirements and determining the sub-element contribution necessary to meet the higher-level requirement.

Many of the lower-level requirements were founded in the analysis work performed in response to the SRR/CoDR analysis plans. Examples from the fluid behavior and LETS analyses include definition of the minimum propellant settling time, the required MPT vortex suppression configuration, and the water hammer pressure capability each hydraulic component must have to survive system operation.

Lower-level component requirements were also established based on the types and general system locations of major hardware items contained in the MPS concept. The activity began with establishing the functional requirements of each element and defining the performance capabilities needed. Table IX provides examples of the relationship between functional and performance requirements on selected system elements. Mechanical interface definition was limited to interface and packaging constraints since components had not yet been selected. Mission-related constraint requirements associated with processing the spacecraft at Cape Canaveral, launch survival, and in-flight operations were defined for each system element along with other constraint requirements such as wire derating, material outgassing limits, and compatibility with thermal bake-out conditions. The requirements were added to the TRD and associated with the MPS system parent requirement. Since EXCEL does not have the capability to link cells like other database tools, the connection was made by identifying the lower-level requirement with the same specification number as its parent and adding a system element description as the unique identifier. Figure 9 shows an example of the flow-down of the system operating life requirement to the MPS thrusters and pressure vessels. Once the lower-level requirements were added to the TRD, specific hardware requirements could be viewed using Excel's filter feature as shown in Fig. 10 for the helium pressurant tank. This capability allowed hardware specific requirements to be sorted and saved as requirement "fly sheets" to support the component competitive bid process. The requirement count for the MPS including requirements assigned to the subsystems, thrusters, pressure vessels, isolation valves, regulators, service valves, filters, check valves, latch valves, instrumentation, secondary structure, thermal management system hardware, and electrical ground support equipment totaled over 1000.

Table IX. Functional and performance requirements for selected MPS hardware.

System Element	Functional Requirement	Performance Requirement Categories
LVA Thruster	Provide impulse for large delta velocity maneuvers, thrust when power is applied to the propellant valves, and steady state and single pulse mode operation.	Thrust, Specific Impulse, Inlet Pressure and MR Range, Throughput, Deep Space Starts, Restarts, Power, Weight, Leakage
ACS Thrusters	Provide impulse for attitude control and unloading of the spacecraft momentum wheels, thrust when power is applied to the propellant valve, and pulse and steady state operation	Thrust, Specific Impulse, Minimum Impulse Bit, Throughput, Cycle Life, Power Weight
LVA-TVC Thrusters	Provide the impulse for propellant settling and small control maneuvers, thrust when power is applied to the propellant valve, and pulse and steady state operation	
Pressurant Bottle	Provide gaseous helium storage	Volume, Leakage, Weight
MPT	Provide storage of NTO or hydrazine	Volume, Leakage, Weight, Expulsion Efficiency
AFT	Provide hydrazine storage and positive propellant expulsion	Total Volume, Propellant Volume, Leakage, Diaphragm Reversal Cycles, Weight

12. Establishing the MPT Nutation Control Features

Subscale drop tests were performed to establish the internal tank features in support of lower-level requirement definition. Although the primary objective of the tests was to establish an internal baffle configuration that resulted in compliance to Boeing's 150-s pre-third stage ignition and 50-s post-burnout nutation time constants, a secondary objective was to establish a baffle configuration that was common to all MPTs. Subscale models were developed to represent the spacecraft and Delta IIH third stage. Both single- and dual-baffle configurations were tested. Dual 178-mm (7-in.) wide baffles were found to be an acceptable solution common to both the oxidizer and fuel tanks. The dual-baffle geometry was then captured as a derived tank requirement.

13. Update Tank Requirements

Tank-level requirements were formalized in a configuration-controlled propellant tank specification and SOW.

14. Establishing Data Deliverables for Procured Items

The data deliverables identified in the MPS SOW were reviewed and derived into a set of general data deliverables for each procured item. The documentation needed to support product certification was also considered. The list of required data deliverables was captured in a non-hardware specific "generic" SOW and readied for the competitive bid process.

15. Component Competitive Bid

The generic SOW along with the all the component specific "fly sheets" were provided to Aerojet procurement. The information was integrated into formal Request for Quotes (RFQs) sent to prospective suppliers. Hardware capability data and cost and schedule quotes were received and presented at PDR.

Parent

Children

Specification Number								System Element	Item No.	Requirement Title	Requirement Value	NA	QT	PF	AT	A	I	S
												Verification Method						
3	5	2	2							Operational Life	The propulsion system shall meet all functional and performance requirements throughout the mission operational life of eight years.						I	
3	5	2	2					LVA Thruster	1	Operational Life	The thruster shall meet all functional and performance requirements throughout the mission operational life of eight years.						I	S
3	5	2	2					LVA-TVC Thruster	1	Operational Life	The LVA-TVC thruster assembly shall meet all functional and performance requirements throughout the mission operational life of eight years.						I	S
3	5	2	2					ACS Thruster	1	Operational Life	The ACS/Anti-Sun thruster assembly shall meet all functional and performance requirements throughout the mission operational life of eight years.						I	S
3	5	2	2					Pro-Sun Thruster	1	Operating Life	The REA shall meet all functional and performance requirements throughout the mission operational life of eight years.						I	
3	5	2	2					Helium Tank	1	Operating Life	The operating life will be a minimum of eight years while in space. The COPV shall maintain functionality and operability following exposure to all loads and pressure cycles imposed on the tank starting from Acceptance testing tomission completion. Reference APSP 48099 for histogram.					A		S
3	5	2	2					Primary Propellant Tanks	1	Operational Life	The operating life will be a minimum of eight years while in space. The tank shall maintain functionality and operability following exposure to the load and cycle histogram defined in Table 3.7.3-1.						I	
3	5	2	2					Auxiliary Fuel Tank	1	Operational Life	The operating life will be a minimum of eight years while in space. The auxiliary tank shall maintain functionality and operability following exposure to the load and cycle histogram defined in APSP-48100.					A		S

System Element Description Used as Unique Identifier

Figure 9. Lower-level requirements were associated with parent requirements.

							Helium Tank		Requirement Title	Requirement Value
3	4						Helium Tank	4	MEOP	The maximum expected operating pressure (MEOP) of the COPV shall be 4500 psia.
3	5	1	1				Helium Tank	1	Dry Mass	The tank dry mass shall not exceed 10.5 kg (23.15 lbm), maximum. The mass shall be measured within an accuracy of 0.5%.
3	5	2	1				Helium Tank	1	Storage Life	The cleaned and protected COPV may be stored in a controlled inert environment for a minimum of 5 years. Materials of construction shall be assessed against potential degradation of performance for long term storage. PSI shall identify any special handling requirements associated with achieving safe storage of the COPV.
3	5	2	2				Helium Tank	1	Operating Life	The operating life will be a minimum of eight years while in space. The COPV shall maintain functionality and operability following exposure to all loads and pressure cycles imposed on the tank starting from Acceptance testing tomission completion. Reference APSP 48099 for histogram.
3	5	5	3	1			Helium Tank	1	Volume	The minimum total volume of the COPV at MEOP conditions shall be 67.3 liters (4105 in3). The minimum total volume of the COPV at ambient conditions shall be 66.2 liters (4040 in3). Volume verification shall be performed at ambient conditions.
3	5	11	1	3			Helium Tank	1	External Leakage	External leakage from the COPV shall not exceed 1.0 x 10 -6 standard cubic centimeters per second of helium gas while at MEOP.
3	10						Helium Tank	10	Pressure Vessel Classification	The COPV shall meet the leak before burst (LBB) criteria for COPVs in accordance with EWR 127-1.

Figure 10. Hardware-specific requirements were sorted into requirement "fly sheets" to support component RFQs.

16. Update Verification Plans

The overall SRR/CoDR-level test approach was maintained at PDR except for the addition of acceptance random vibration testing for the system check and pyrotechnic isolation valves based on SRR/CoDR review board recommendations. The test matrix was translated into an overall master inspection and test plan that tied the tests with specific points in the MPS build. It also was expanded to identify the system level at which specific workmanship inspections or tests were performed. Fig. 11 shows an example of the overall plan that provided the roadmap for drawing and test procedure development.

System-level analysis plans were either implemented as planned or expanded. The fluid behavior analysis was performed in accordance with the SRR/CoDR plan and completed during this program phase. Propellant slosh characteristics and models were established. The MPT vortex suppression configuration was defined. Propellant settling trades were performed. The selected baseline propellant settling approach used two C-thrusters firing at a 100 percent duty cycle; however, following MPS delivery, this was changed to four ACS thrusters when JHU/APL determined that the C-thruster plumes created torques around the spacecraft X-axis beyond control authority of the ACS thrusters.

Additional fidelity was added to the remaining analysis plans. The most significant expansion occurred with the system performance analysis plan. In addition to the plan objectives identified at SRR/CoDR, some specific operational cases were added. These cases ranged from establishing start/shutdown/transient system characteristics; evaluating the system's capability of providing propellant to the LVA and monopropellant thrusters at conditions within the thruster's qualified pressure, temperature, and, for the LVA, mixture ratio ranges; and characterizing auxiliary tank refill operations. System and derived requirements to be verified by these analyses were also added to the plan. Finally, quantified parameters representing the pneumatic/hydraulic and operational characteristics of MPS hardware elements were established. Although the overall structural analysis plan previously described in Table IV was unchanged, minor adjustments to the specific structural requirements were made, primarily due to defining the loads and structural criteria for the newly defined MPT internal features. Finally, a preliminary analysis plan directed at assessing NTO diffusion characteristics was drafted for later implementation when the system design had further matured.

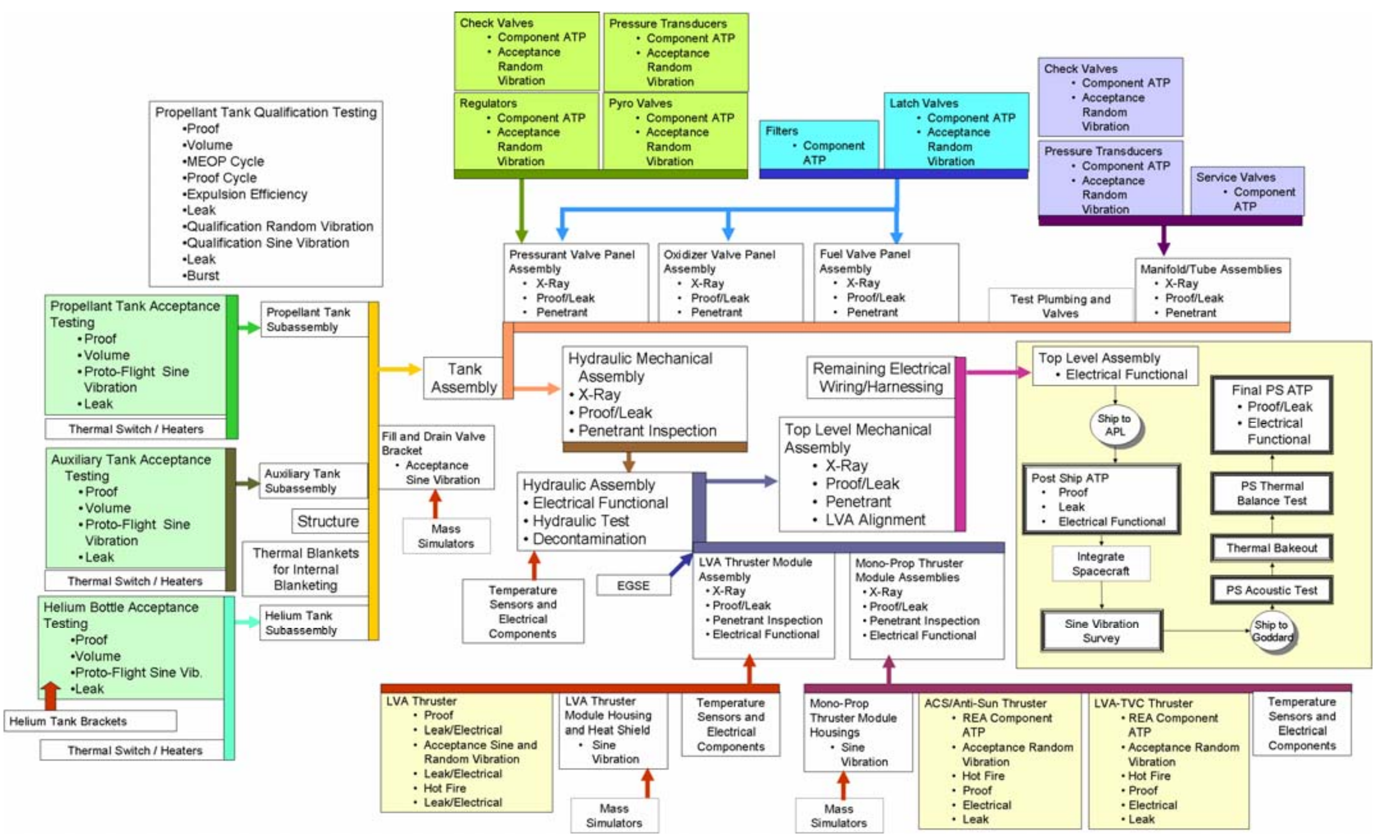

Figure 11. Master Inspection and Test Plan.

SE Status at PDR

By MPS PDR, the MPT tank requirements were complete, and a clear set of derived requirements were established and captured, first in the MPS TRD, and subsequently in a tank-specific SOW and specification. More than 1000 system and lower-level requirements were established. SRR analysis plans were completed or expanded to include more detail. An NTO diffusion control plan was initiated. The master inspection and test plan was established to define the system level at which specific tests were performed. Finally, the component technical and data requirements were communicated to potential suppliers in the form of RFQs, and bids were received and reviewed.

C. PDR to Critical Design Review (CDR)

During the PDR to CDR time frame, the SE process shown in Fig. 12 guided MPT design development, supplier and part selection, component design verification, and design and analytical verification of the system. The SE roadmap was unchanged from PDR with the exception of modifying select lower-level requirements to reflect the capability of down-selected hardware and minor adjustments to analysis plans.

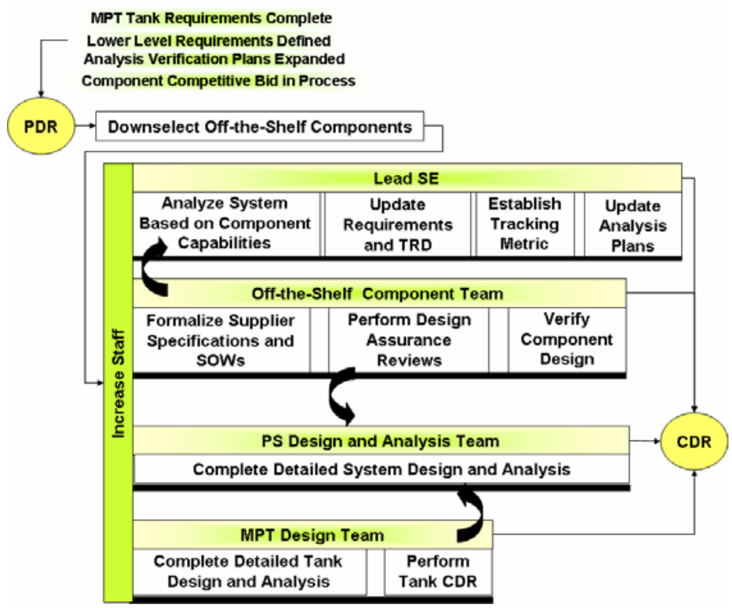

Figure 12. SE process from PDR to CDR.

17. Off-the-Shelf Component Down-Select

MPS component selection was based on technical performance, mass, power, cost, and lead time based on information in the supplier proposals.

18. Increased Staffing

Up to this point, the program had been run by a small technical, program management, and procurement staff. However since this program phase would go beyond the planning and into the program execution phase, additional personnel were added to support component procurement, system analysis, and detailed design. Fig. 12 depicts the interrelationship between each activity. Although multiple SE-related activities were conducted in parallel, the path forward and demarcation of responsibilities were well defined as described below.

Lead Systems Engineer

The lead Systems Engineer's responsibility was to provide oversight for all SE-related activities performed during this program phase. The lead was responsible for evaluating all potential requirement compliance concerns that surfaced from the various MPS development activities for impact on system compliance. Adjustments to requirements were needed in some instances due to the capability or characteristics of the selected system hardware. The lead was also responsible for maintaining the TRD and establishing and maintaining a requirement verification tracking plan. Figure 13 shows the final version of the plan. Finally, the lead Systems Engineer was responsible for updating analysis plans as required and reviewing compliance documentation. Additional analysis plans were developed such as the thruster plume analysis plan. The objective of this plan was to predict the moments imparted to the spacecraft due to LVA thruster plume impingement on the spacecraft sunshade. The system performance analysis plan was again updated to replace the assumed pneumatic/hydraulic and operational characteristics of MPS hardware elements with the actual capabilities of the selected components.

Off-the-Shelf Component Team

The team responsible for procuring the MPS off-the-shelf components consisted of personnel from Aerojet's engineering, quality, and procurement groups. The engineering team members were provided with the original requirements and SOW used during the RFQ and the proposal from each selected supplier. Their immediate task was to develop a formal technical specification and SOW to be contractually levied on each vendor. Since the hardware capability did not always reflect the requirements specified in the "fly sheets," the team was tasked with developing a capability-based specification and coordinating the information with the lead Systems Engineer for system impact. Once the requirements and scope were reconciled, the component team put each component-specific

SOW and specification under configuration control and established a component-specific TRD based on the released specification. Each component supplier conducted a design assurance review (DAR) that presented the design verification information associated with their part. Detailed verification reports were provided to Aerojet for an independent assessment. Upon approval, the documents were formally issued and the component TRD was updated to capture the information needed for product certification. Since the hardware were still being fabricated, the only verification tasks remaining were those associated with inspecting and testing each delivered item.

MPT Design Team

The main propellant tank design team included ATK's program management, engineering, and manufacturing staff with oversight from members of Aerojet's MESSENGER engineering, quality, manufacturing, and procurement team. Additional support was provided by APL's design and structural analysis staff. The analytical effort focused on completing structural, fracture, and safe-life analyses. The design effort focused on completing the detailed design and the accompanying design disclosure information. The analysis results and design disclosure were presented at the MPT CDR which was held prior to the MPS CDR. Detailed verification reports were submitted. Upon approval, the documents were formally issued and the TRD was updated to capture the information needed for product certification. By MPS CDR, the design was analytically verified in accordance with MPS requirements and ready for fabrication and test. Figure 14 shows the post fabrication qualification and acceptance tests planned for the MPT. Additional detail on the design and development of the MESSENGER main propellant tank can be found in Reference 2.

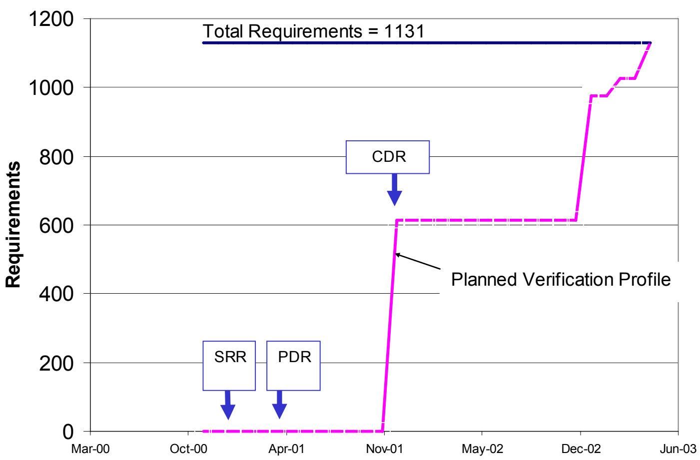

Figure 13. Requirement verification tracking plan.

The MPS Design and Analysis Team

The MPS detailed design team included engineering, manufacturing, and quality personnel. Their responsibility focused on completing the detailed design and preparing for the build phase. Establishing the detailed design included packaging of the selected components in addition to the MPT, performing regular model-based MPS/structure interface checks, preparing and releasing engineering drawings, and completing the remaining CDR-level system analyses. CDR-level system analyses were completed and supported the conclusion that the MPS met requirements. For example, LETS analyses verified that the MPS provided propellant inlet conditions to the 4.4-N, 22-N, and LVA thrusters within their qualified conditions. Mission analysis verified that the thruster performance requirements specified to each MPS thruster were sufficient to meet the mission profile. Mass properties and center-of-gravity analysis verified that the as-designed MPS met all mass property related requirements. Manufacturing flow

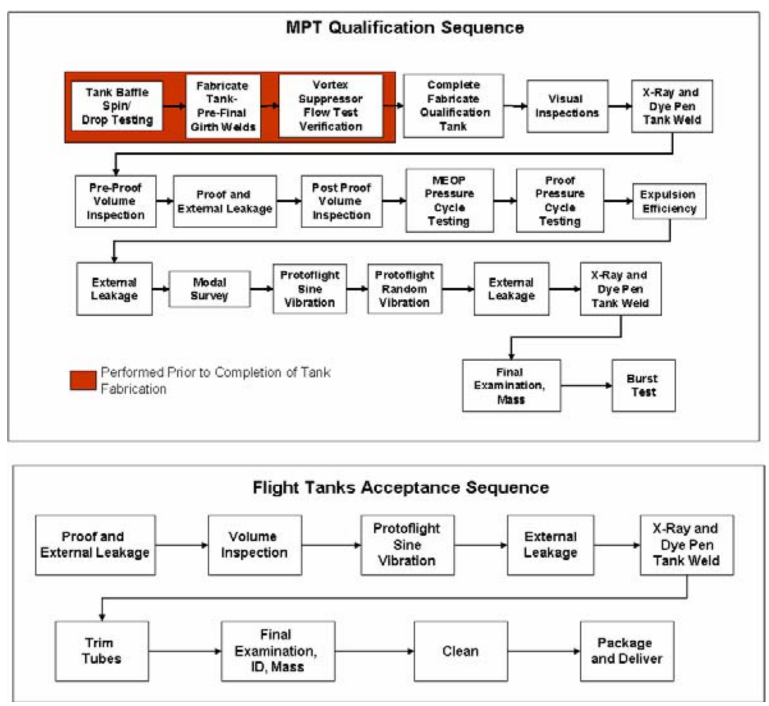

Figure 14. MPT qualification and acceptance test sequence.

plans and test sequences were established in preparation for fabrication. Draft versions of system-level test plans were established as well.

Status at CDR

By CDR, the designs of all off-the-shelf components were verified to meet specified design verification requirements and the deliverable units were being fabricated. The MPT and MPS designs were analytically verified. Drawings were ready to be converted to manufacturing planning for the fabrication, test, and certification phase of the program.

D. Fabrication, Test, and Certification

The SE focus during the fabrication and test phase was to complete verification, develop the product certification report, and gain APL acceptance of the system. Three formal product certification reviews were planned as shown in Fig. 15.

The Phase I review was led by the MPS engineering team and focused on APL acceptance of the procured hardware. Detailed component data books were prepared that contained all pertinent design disclosure data such as the specification, SOW, interface control drawings, analysis and qualification documentation, and copies of the acceptance data packages that formed each component's end item data package (EIDP). Also included were hard copies of the component specific TRD in the product certification report format and cross-references to the parent requirement in the MPS TRD. The Phase II of the MPS certification addressed the as-fabricated system and was led by the quality organization. Phase III focused on accepting the MPS based on final system level testing and was led by engineering. The MPS completed certification ahead of schedule as shown in Fig. 16 and was delivered to JHU/APL on time.

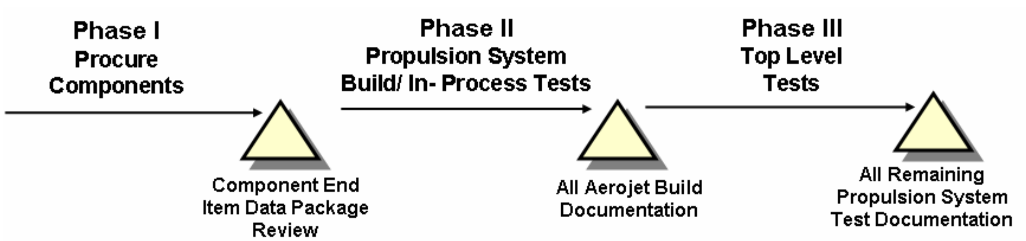

Figure 15. MPS time-phased product certification plan.

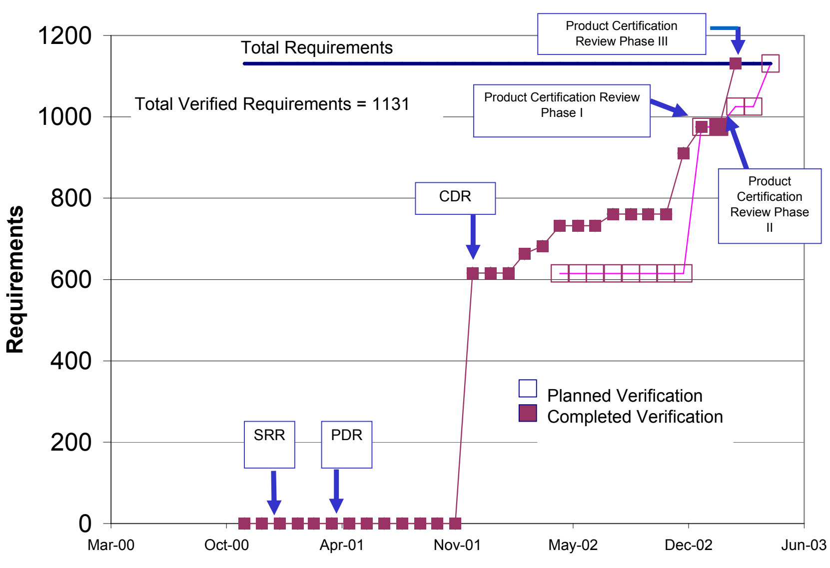

Figure 16. MESSENGER MPS was certified ahead of schedule.

VI. Conclusion

The process of early definition of requirements and verification planning, early focus on risk reduction, and understanding system characteristics positioned the MESSENGER MPS team for success. The optimum system and tank concepts were selected. Program approach changes were discovered early, and the proper adjustments were made without undue cost or schedule impact. Test and analysis approaches established prior to SRR/CoDR were maintained throughout the program with few modifications. RFQs for procured hardware were sent out for competitive bid with a high-quality requirement and data deliverable set, resulting in little vendor cost growth. Staffing was increased after planning had been performed and team members were armed with detailed requirements, task objectives, and expectations leading to successful plan execution. The MPS and all MPS components were verified to meet both design verification and acceptance-level requirements. The MPS was delivered on time and within budget. It was successfully integrated with the MESSENGER spacecraft, launched on the Delta IIH in 2004 (where it demonstrated acceptable nutation control during third stage operation), and has performed nine propulsive maneuvers to date.

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