Mars Science Laboratory Focused Technology Program Overview

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Abstract— As part of the ongoing NASA Mars Exploration Program (MEP), the Mars Science Laboratory (MSL) Project is an innovative mission launching in 2009 to deliver a new generation of rover safely to the surface of Mars and conduct comprehensive *in situ* investigations using a new generation of instruments. The MSL rover will be designed to land with precision and be capable of operating over a wide range of Martian terrain for an extended period. The MSL Focused Technology (FT) program functions within MSL and is responsible for developing the wide-range of technologies needed for the MSL mission.

This paper describes how the MSL-FT program functions to ensure that the needed technology is identified, developed, matured to TRL 6, and infused in the MSL mission, in a systematic fashion that will meet the mission's objectives innovatively and within budget. The paper describes the mission's technical and project challenges, and outlines the process, procedures, tools and people involved in meeting those challenges. The paper also discusses the technology certification process required to demonstrate that technology deliverables perform adequately and in a predictable fashion to successful infusion into the MSL Flight System.

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1. INTRODUCTION

As part of the ongoing NASA Mars Exploration Program (MEP), the Mars Science Laboratory (MSL) Project is an innovative mission launching in 2009 to deliver a new generation of rover safely to the surface of Mars and conduct comprehensive *in situ* investigations using a new generation of instruments. The MSL rover will be designed to land with precision and be capable of operating over a wide range of Martian terrain for an extended period. The innovative MSL project will increase our understanding of the Martian environment in ways that prior missions have not been technologically equipped to accomplish, and will introduce new capabilities to support NASA's scientific goals into the next decade of exploration. These new capabilities will include: 1) the ability to land safely at many desired localities on Mars, and 2) the ability to operate an analytical *in situ* science laboratory on the surface of Mars. Both of these new capabilities will carry forward into future missions. The MSL Focused Technology (FT) program functions within MSL and is responsible for developing the wide-range of technologies needed for the MSL mission.

MSL-FT is in place to facilitate the process of new technology entering the project, including definition, selection, management, infusion and assessment [1]. The MSL-FT program serves as a bridge across science, technology, project, and operational systems to coordinate, synthesize and distill the contributions of each of these key areas to the development and implementation of critical mission capabilities. Primary goals of MSL-FT are to: 1) Increase state-of-the-art (SOA) performance, 2) Reduce cost, and, 3) Mitigate risks. Additionally, MSL-FT program is in place to increase the long-term capability of future MEP missions.

Since the inception of MSL-FT in early 2003, the MSL flight system baseline design has gone through several iterations, and the late-2004 baseline design reflects a more mass/power/cost-efficient configuration resulting in a 500kg-class rover instead of the original 900kg rover design. In response to the baseline design changes, MSL-FT underwent several realignments where some existing tasks were descoped/rescoped and new ones were created. , Technologies that have survived these realignment activities have demonstrated their utility and importance to MSL—this parallels the "survival of the fittest" evolution process.

This paper describes how the MSL-FT program functions to ensure that the needed technology is identified, developed, matured to TRL 6,[1] and infused in the MSL mission, in a systematic fashion that will meet the mission's objectives innovatively and within budget. The paper describes the

[1] Technology Readiness Level (TRL) is a systematic metric/measurement system that supports assessments of the maturity of a space technology and provides a method of comparing maturity between different types of technology. The TRL scale is from 1 to 9, where 1 represents a technology principle and 9 represents a technology flown successfully in space. TRL 6 corresponds to a technology functioning in a subsystem (model or prototype) in a relevant environment (ground or space).

mission's technical and project challenges, and outlines the process, procedures, tools and people involved in meeting those challenges. The paper also discusses the technology certification process required to demonstrate that technology deliverables perform adequately and in a predictable fashion to successful infusion into the MSL Flight System.

2. Major Technology Investments

The major investment items of MSL-FT are focused on providing new capabilities for MSL technology in two primary areas: 1) Entry, Descent, and Landing (EDL) and 2) Surface Systems. New EDL capabilities include hypersonic aeromaneuver guided entry and Skycrane-based powered descent and landing. Surface system technologies support the long-life (1 Earth year) and long-range mobility (5km – 10km) operations of MSL.

MSL EDL Methodology

In order to achieve precision landing (i.e., smaller landing ellipse 10×20km, 3-sigma), a lifting entry vehicle and an EDL guidance/control system are being developed. These technologies will operate from the point of entry to the point of parachute deployment and are designed to address uncertainties in the entry conditions, atmospheric density profile, winds, and aerodynamic performance. The powered descent phase will commence after the parachute is jettisoned—initiating the Skycrane landing approach. The skycrane is capable of efficiently/safely landing a large payload on Mars using a propulsion system mounted on top of a rover and releasing the rover slowly via a descent-rate-limiter umbilical at the beginning of the powered descent phase and slowly lowering the rover to the surface. Figure 1 depicts the new EDL methodology being developed for MSL.

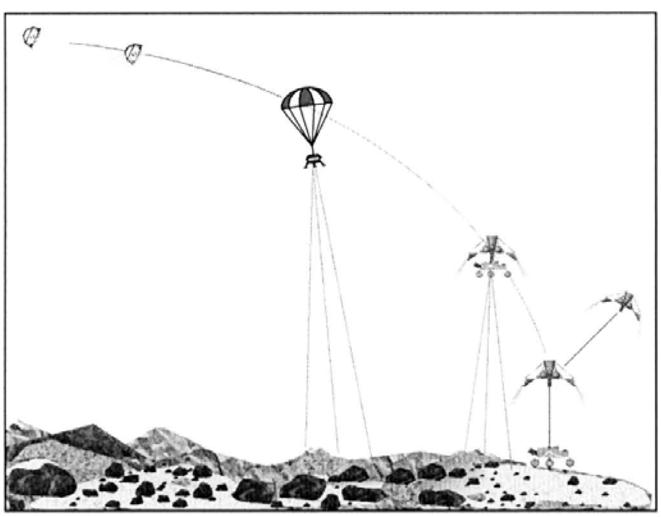

Figure 1 - MSL Entry, Descent, and Landing Approach

Mars Lander Engine

Improved descent propulsion (400N-3000N throttled) is achieved by upgrading the Viking lander descent engine technology via a change from a multi-nozzle configuration to single nozzle (improved performance) and improved materials in the cat-bed cylinder design. In addition, the new throttle valve is based on a cavitating venturi design and is adopted to simplify operation, reduce feed system coupling, and eliminate water hammer concerns. Figure 2 depicts the Viking derivative engine with new throttle valve.

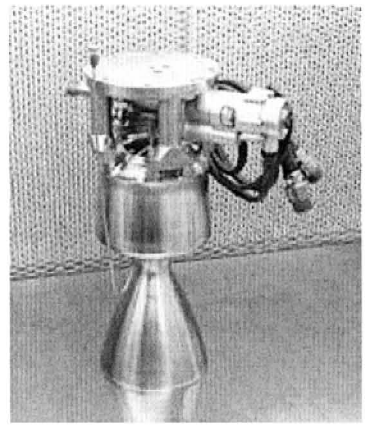

Figure 2 – Viking-derivative Engine Assembly

Long-life, Extreme Environments Actuators

MSL has long-life and extended mobility range requirements that require new technologies to accommodate an integrated flight actuator (i.e., motor, gearbox, sensors, and drive electronics). Figure 3, shows the integrated flight actuator needed to extend the mechanical life of the mission by a factor of 20 beyond current actuator capabilities while surviving/functioning in the Martian environment without the need for thermal control. The advanced technologies selected include brushless dc motor with Hall sensors for winding commutation, low-temperature/low-mass gearbox, and chip-on-board electronic packaging.

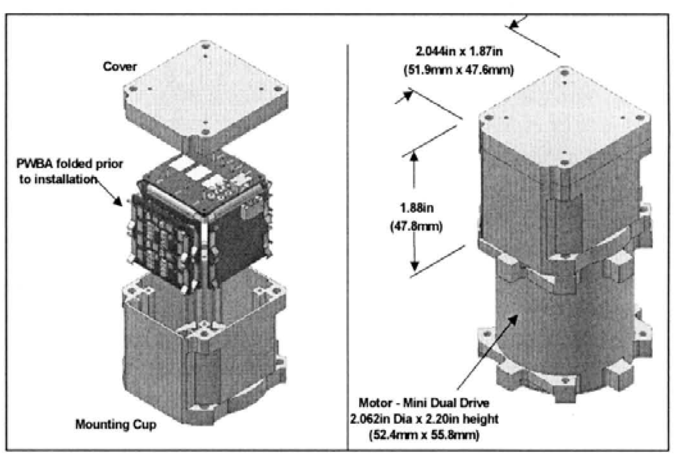

Figure 3 – MSL Flight Actuator Assembly

Sample Acquisition/Sample Processing and Handling

In addition to longer life and greater mobility capability, MSL will have a comprehensive science payload and analytic laboratory that will analyze chemical and isotopic composition of gas, rock and regolith samples, and provide definitive mineralogy and high-resolution textural information. Payload engineering support includes the development of new technologies for MSL Sample Acquisition/Sample Processing and Handling (SA/SPaH), see Figure 4. A full-scale SA/SPaH subsystem includes single manipulator, end effector with corer/abrader, rock crusher, and sample capture trays with door as well as a bio-Barrier concept integration and self-cleaning mechanization for cross contamination.

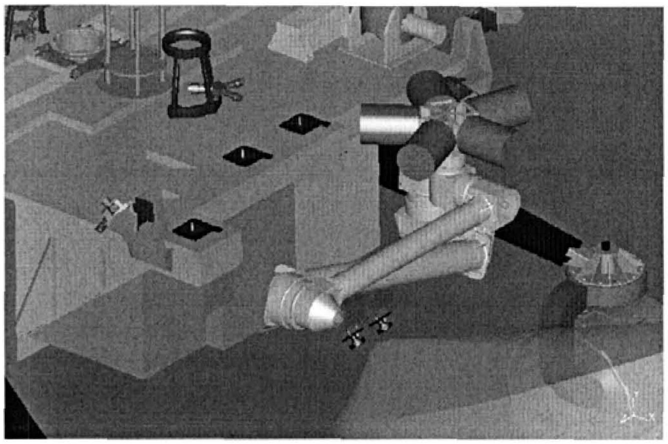

Figure 4 – MSL SA/SPaH System

Advanced Rover Technologies

Advanced rover technologies will be required to increase the MSL science return per sol and to assure vehicle health via on-board diagnosis and health monitoring. More specifically, technologies will be required that enable 100s of meters of autonomous traverse per command cycle with 6km total traverse for the mission, and the ability to place a science instrument from a 10m standoff with an accuracy of 0.1% (or 1cm). Figure 5 depicts various rover technologies employed to validate the rover navigation and instrument placement capabilities proposed for MSL deployment.

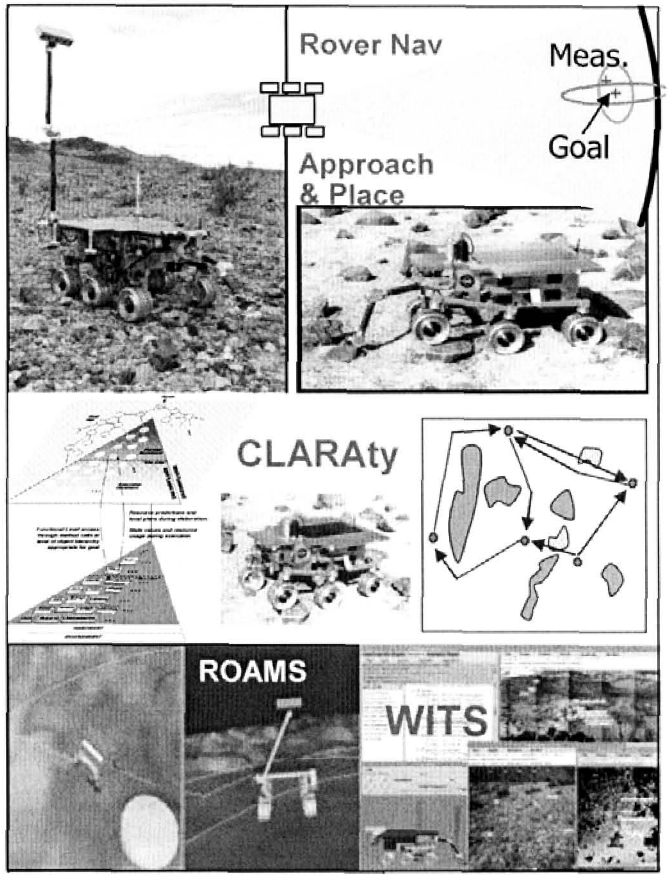

Figure 5 – Advance Rover Technologies for MSL

Mobility Technologies

Because of the MSL-unique landing and drive away architecture, new lightweight designs are required for wheel structure and differential components, these designs need to incorporate a landing-capable suspension system with appropriate stiffness and flight-like kinematics. The lightweight wheel design (see Figure 6) must incorporate flexible elements to limit loads into the suspension/drive actuator and provide adequate ground pressure and traction in sand and rocks. Early prototyping of a full-scale vehicle is planned to demonstrate the vehicle system's capabilities in meeting MSL landing and extreme terrain traverse requirements.

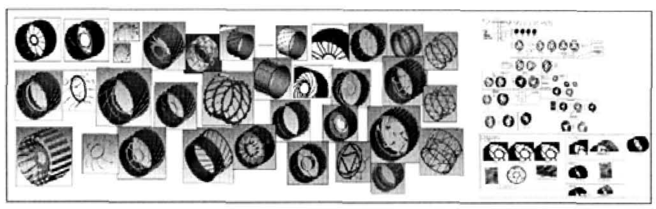

Figure 6 – Lightweight Wheel Design/Characterization

Integrated Simulations

A comprehensive suite of simulation tools for EDL/Rover GNC analysis, flight software V&V, and real-time hardware-in-the-loop testing is needed for MSL. This distributed multi-platform simulation architecture (Figure 7) addresses closed-loop dynamics simulation as well as bit-level simulation.

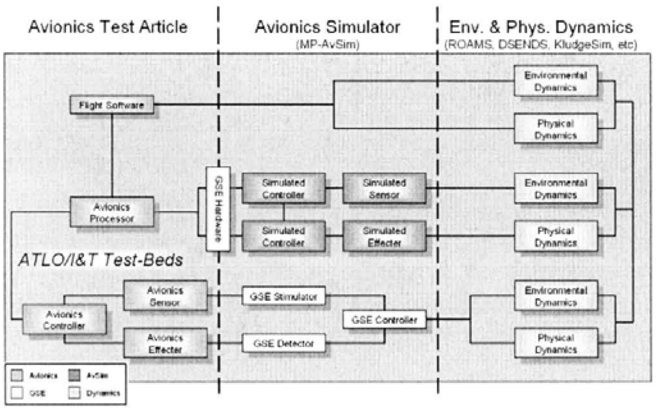

Figure 7 – Multi-Platform Avionics Simulation

3. PROGRAM ORGANIZATION/MANAGEMENT

At present, the MSL-FT program is organized into five different elements: 1) EDL, 2) Surface System Hardware, 3) SA/SPaH, 4) Surface Ops, and 5) MTP Advanced Technology Infusion.

EDL tasks address guided entry, aeroshell and thermal protection system, propulsion system, and safe landing.

Surface system hardware tasks include long-life actuator assembly, extreme environment electronic parts and packaging designs, thermal control systems, and mobility technologies.

SA/SPaH tasks incorporate development/integration of single manipulator with end effector, corer/abrader, rock crusher, and manipulation arm control system as well as bio-Barrier concept integration and self-cleaning mechanization for cross contamination.

Surface ops tasks involve validations of rover navigation and instrument placement technologies, prototyping of a streamlined activity planning and sequencing subsystem, and integrated simulation.

MTP advanced technology infusion tasks combine required infrastructure tasks supporting integration/validation of rover technologies as well as various technology development efforts previously planned to be infused into MSL that have been deemed extremely beneficial to future mars missions (e.g., Subsonic parachute and micro sun sensor developments).

Five Element Managers report to the MSL Technology Manager. The Element Managers are responsible for major systems in the project and ensure that the technologies under development are compatible with the latest mission concept. They also ensure that the mission concept is consistent with the progress of the different technology tasks.

The MSL Technology manager reports to both the Mars Technology Program (MTP) manager and the MSL Project manager. The MSL Project manager ensures that the technology meets the MSL requirements, and the MTP manager ensures that the technology meets the long-range requirements of MEP. This relationship – which involves inherent conflict -- benefits the MSL project, the FT program and the larger MEP, by providing a check-and-balance process to many budget decisions.

MSL Technology Manager

The MSL Technology manager has day-to-day responsibility of managing the MSL-FT program with guidance provided by both the MSL Project manager and the MTP manager. The MSL Technology manager reports to these managers on a regular basis and discusses technical progress, cost, and schedules of the different technology tasks. Specific responsibilities include: coordinating and leading activities in the overall technology effort; supporting Project Office activities; organizing and convening monthly management reviews (MMRs); supporting quarterly reviews; and supporting year-end reviews.

MSL-FT Element Manager

The Element manager reports to the Technology manager. The MSL Project manager and the MTP manager appoint the Element managers. The primary role of the Element manager is to provide system engineering across the different technologies within their element. An Element manager is typically a project person who provides technical oversight of the tasks in their area. Specific responsibilities include: coordinating the system engineering activities in their designated technology areas, balancing the tradeoffs between the different technologies within their area or element; understanding how their technologies impact the project concept and how the maturing project concept impacts their technologies; supporting the MSL Technology manager; conducting weekly technical meetings to assess their technologies; supporting monthly management reviews and submitting monthly progress summaries; supporting quarterly reviews; and supporting MTP year-end reviews.

MSL-FT Task Manager

Each MSL-FT element includes several tasks, managed by Task managers. Each task is required to develop a Technology Development Agreement (TDA) and a financial budget. The TDA is written by the Task manager and is approved by the Element manager, the appropriate line manager, and the MSL Technology manager. The Task manager's responsibilities are to: plan the task including defining performance goals, and risk, cost, and schedule assessment; assemble task members (JPL, NASA centers, universities, etc.); lead the technical development; participate in weekly, monthly, quarterly, and year-end reviews; provide support to the Element manager, and deliver technology products to the Element manager.

Technology Development Agreement (TDA)

Once a technology task has been selected, Task managers and their Element managers develop TDA's. A TDA documents the plan to mature a technology from its current TRL to TRL 6. They also contain specific test protocols for each TRL transition as well as the associated costs, schedules, and facilities to achieve each TRL transition. These TDA's and their related test protocols represent a process that is performance-oriented and paced by the TRL transitions.

The MTP TDA system is a web-based technology management tool that captures the technical and programmatic information related to a technology task. NASA Headquarters requires JPL and other NASA Centers to complete an annual technology inventory. While serving as a blueprint to technology maturity, the TDAs also capture the information required by NASA's technology inventory.

The TDA process is initiated by the Program Manager by defining the default structure for Funding Programs and Implementing Programs. The default structure process is prompted when the Program Manager inputs the following information into the TDA system:

- TDA ID
- Inventory ID
- Title
- Task Manager
- Program Office
- UPN
- Funding Program
- Funding per Fiscal Year

Once this information has been input, each Task Manager is notified that a TDA has been started for their task, and that they need to enter the balance of information concerning the tasks.

The data entered by the Task Managers into the TDAs include:

Introduction—Describes the technology, assesses the state-of-the-art, and defines the current Technology Readiness Level (TRL).

Objectives—Describes the task's technical objectives and goals. In addition, this field defines the specific mission requirements this task will enable.

Technical Approach—Describes the methodology and approach to conduct the proposed development. Defines the products and/or expected results. Provides information on technology development approaches such as analysis, experiment, field testing, and, if applicable, flight validation.

Significance—Explains in what way this task will contribute to a NASA Mission. Examples are mission enabling, mission enhancing, increasing safety margin, reducing mass, lowering mission cost, etc. Mentions possible applications to other missions. Describes the technology's current performance level and what level of performance the new technology will achieve.

Milestones and Deliverables—Identifies the dates when major milestones will be achieved. At least three milestones are required in each fiscal year of the task. The list includes events, dates, and descriptions.

Funding Distribution—Lists the type of budget elements (people, parts, etc) being funded, which fiscal year, the yearly totals, and the total to complete. This field is completed after the Task manager completes the budget estimate tool (Friendly Front End aka FFE).

Partnerships/Cooperative Agreements—Describes any formal partnerships, cooperative agreements, or other agreements that involve this task. However, proprietary or partner-sensitive information are not to be included in this field.

Comments—This field answers the following questions (as appropriate):

1. What is the impact if funding is increased by 20% and decreased by 20%?
2. What are the priorities of the different sub-tasks?
3. What is the task's probability of success and the backup plan if not successful?
4. How is this technology dependent on other development efforts?
5. Can the technology scale for different configurations and if so, what is the impact on mass and power?
6. What are the technology's interfaces and are they standard (if appropriate)?
7. Describe any out-of-house efforts related to this task and at what level of funding.
8. What procurements are planned and what is the acquisition plan?

Infusion Plan—Defines the plan for applying the technology developed in this task to a practical implementation. Final implementation includes either a flight project or a ground application.

Reporting Plan—Defines the plan for reporting status/progress on this task to management. This should include task reviews, non-advocate reviews, project review, written reports and publications.

Commercialization Plan—Defines the plan for transferring the technology developed in this task to commercial use. If appropriate, this field identifies the industry partner teaming on the commercialization effort. If the technology has no commercial potential, this field contains a "N/A".

Approval—The TDA sequence of approval is: Task Manager, Section Manager, Element Manager, and the MSL-FT Technology Program Manager

Other members of the project team review the technologies at the initial proposal review and again during periodic status reviews. After the TDA is approved, the Project implements the technology development task. The TDA is now under Configuration Management control and any future changes will require MSL Technology Change Request (TCR) approval. While TDA's are open to review and changes at any time–within the TCR approval process – they are minimally reviewed at the end of every fiscal year to ensure they reflect current technology and project needs.

4. REVIEW PROCESSES

TCR Review/Approval

As the MSL technology tasks proceed and as the MSL Project concept matures, changes to the technology tasks are inevitable. In addition, the MSL technology program is managed by both the MSL Project and the MTP Program, each with a slightly different focus. The focus from MSL is directed at optimizing the project, while MTP focuses on program optimization. The technology change control process was established to involve all impacted parties in the change process and to balance the healthy tension between the MSL project and the MTP program.

The change process is initiated when a Task Manager drafts a Technology Change Request (TCR) form. The TCR is developed with and approved by both the Task Manager's line management and Element Manager. The Line Manager and the Element Manager ensure that the change is consistent with project's needs and the functional organization's ability. Once initiated, the TCR will follow one of three basic paths: a) Reviewed and approved by the MSL Technology Manager, b) Reviewed but not approved by the MSL Technology Manager, or c) Reviewed first by the MSL Technology Manager, who elects to convene a discretionary Tech Change Board session to further evaluate the TCR for approval. The MSL Technology Manager holds final approval authority for all FT liens.

The TCR evaluation by the MSL Technology Manager includes a review of the impact on the project's budget, schedule, and performance of the change being requested. At this point, the MSL Technology Manager may decide that the requested change is too significant or controversial for immediate approval. In this case the Technology Manager may elect to convene the Tech Change Board (TCB) to assist in the final determination of a TCR's approval status, see Figure 8.

The TCB is convened by the MSL Technology Manager when the need for further input to resolve any open TCR is identified. The TCB provides a secondary review process to strengthen the MSL-FT's systematic manner of TCR review, which is structured to determine each TCR's impact on the project's risk, cost, schedule, and performance profile. The TCB ensures that all affected parties are cognizant of the change and have a voice in the decision making process. The MSL Project Manager and MTP Program Manager chair the Technology Control Board and have authority to approve any changes that do not affect the projects Level 1 requirements. Advisor members of the TCB include the MSL Technology Manager, the Element Managers, and the project Chief Engineer.

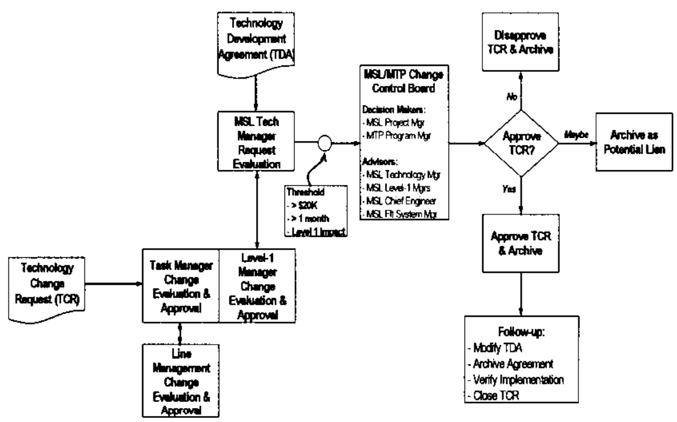

Figure 8 – Technology Change Request Approval Process

Management Reviews

Regular management reviews of programmatic, financial, and technical status are conducted. Major topics to address include:

(1) Progress during past reporting period vs. plan.

(2) Discussion of activities accomplished and not accomplished.

(3) Discussion of problems, concerns and recovery plans.

(4) Schedule status and variance from baseline discussion.

(5) Cost discussion, including comparison of actual and planned cost and an explanation of any variances.

(6) Technical/design status, major technical issues and risks, waivers, and problem/failure report status.

(7) Implementation progress, including procurement and subcontract status.

MTP requires an independent task review process, separate from the MSL MMR process. This separate review process is the MTP Year End and Quarterly Reviews. In the months during which the MTP Quarterly reviews take place, FT Element Managers present the FT status summary of the FT tasks in their area under the MTP quarterly venue. These status summaries take the place of standard MSL-FT MMR's during MTP Quarterly review months. These reviews, conducted by the Mars Technology Program, include reviews internal and external to JPL and the Mars Program. They provide an independent assessment of the MSL technologies with an eye on the big picture.

The MTP Year-end Review (YER) process reviews the status/progress of MSL-FT task-by-task and may result in tasks being recommended for cancellation or tasks placed on hold in order to get refocused. Tasks may be cancelled based on criteria that assesses the task to be ineffective and/or no longer relevant. Tasks that are required to refocus their efforts need to discuss implementation options with internal and external organizations, conduct trade studies, and plan for a delta-review of the task before proceeding. Most of these tasks may receive a low-level of funding while they develop their concepts, complete trade studies, and create new implementation plans.

Peer Review

Peer reviews, or reviews by a small group of experts in systems and relevant mission areas are held in order to increase review depth, assess systems implications, and increase the effectiveness of the major reviews. The use of experts external to JPL is encouraged in these reviews. It is suggested that Peer reviews, which may be conducted as workshops, be used as an interim tool for resolution of technical issues. Since peer reviews are intended to be informal, they are not subject to all the requirements of formal project reviews. However, peer reviews do comply with the following:

(a) Peer reviewers may not be currently working in the major task element under review.

(b) The Element Manager may establish plans for the use of peer reviews

(c) Results of peer reviews shall be documented.

(d) The results of peer reviews shall be discussed at the management reviews.

As peer reviews are not formal reviews, any actions identified are considered advisory.

5. Technology Infusion

The Technology Readiness Level (TRL) scale is from 1 to 9, where 1 represents a technology principle and 9 represents a technology flown successfully in space. Generally, only technology demonstration missions will accept the risk of including a technology with a TRL of less than 6 in their design concept. TRL 6 corresponds to a technology functioning in a subsystem (model or prototype) in a relevant environment (ground or space).

Before being considered for flight implementation, all deliverables from MSL-FT must go through the Technology Readiness Certification Requirements (TRCR) process in order to certify the technology's maturity.

Technology Readiness Certification Requirements

Technology maturity for all deliverables from MSLFT to the MSL project must be certified through Technology Readiness Certification Requirements (TRCR) process. TRCR Boards are convened by FT Element Managers and are chaired by Receiving/Beneficiary Subsystem Project Element Managers.

The purpose of the TRCR form is to assess the readiness of a new flight technology for infusion into the MSL mission. Using the NASA definitions for Technology Readiness Levels (TRL), MSL-FT has established a more in-depth set of requirements for hardware and software developers. By establishing requirements for the technologists and regularly assessing the progress against those requirements, the Project is able to assess the maturity, the developmental risk, and any system implications that this new technology poses to the mission and respond accordingly.

The technology developers also benefit, by having clear knowledge of expectations. The TRCR form is modeled after the formal hardware and software certification that occurs when flight hardware is delivered for spacecraft integration and test though the maturity levels are lessened accordingly.

TRCR-Hardware

Maturity criteria—Hardware

- **Design**
  - Drawings
  - Materials/parts selection
  - Analyses - Thermal, loads and accoustics
  - CG, Mass, Volume, and Power estimates
  - Performance (improvement) estimate
- **Fabrication and Assembly**
  - Fab instructions
  - Flight-like materials used
  - Inspection
  - Unit assembled in flight-like configuration
  - Mass, CG properties
- **Test (after application of power)**
  - Performance/functional testing
  - Environmental testing
  - Power measured
  - Idiosyncracies documented

TRCR-Software

Maturity criteria—Software

- **Design**
  - Performance estimate
  - Functional description documents
  - CPU, memory utilization
  - Source code/algorithm descriptions
  - Test Cases
- **Fabrication**
  - Flight-like development environment
  - Flight approved compiler and libraries
  - Flight computer/OS compatible
- **Test**
  - Executed on flight-like hardware and OS
  - Performance/functionality demonstrated
  - Measured CPU, memory utilization
  - Idiosyncrasies documented

6. Conclusion

The MSL Focused Technology Program is providing time-critical deliverables for infusion into the 2009 Mars Science Laboratory mission. Critical technologies for this mission are: EDL, long-life actuators, mobility technologies, SA/SPaH, advanced rover technologies, and integrated simulation.

The plan is to reach TRL 6 for each technology by the mission's PDR using the established plan to review and certify each technology's maturity level. This program transcends the usual gulf between technology and projects by vertically integrating the technology work with pre-project development in a project-like environment with critical dates for technology infusion. The MSL Technology Program is tightly coupled to the MSL mission and its milestones. This coupling presents a considerable management challenge around dealing with the continual program realignments and responding quickly and effectively to the changing MSL baseline designs typical of the early Project design phase.

References

[1] Robert T. Caffrey, S. Gabriel Udomkesmalee, and Samad Hayati, "Initiating the 2002 Mars Science Laboratory (MSL) Focused Technology Program," 2004 IEEE Aerospace Conference Proceedings, March 2004.

Biography

Dr. Udomkesmalee *received his Ph. D. degree in Systems Science from University of California, San Diego and has over 20 years experience in line/project management, systems engineering, and control system design. As an employee of the Jet Propulsion Laboratory, Dr. Udomkesmalee has worked on a variety of R&D and flight projects including AFAST, VIGILANTE, Galileo and Cassini. Currently, he manages the MSL Focused Technology program. Dr. Udomkesmalee has over 40 publications in the areas of spacecraft/missile guidance and control, GPS systems, celestial sensors, image processing and automatic target recognition.*

Dr. Samad Hayati *works at Jet Propulsion Laboratory in Pasadena California where he is the manager of the Mars Technology Program (MTP). Samad has M.S. and Ph.D. in Mechanical Engineering with a specialty in controls from the University of California at Berkeley. Since 1979 he has been with the Jet Propulsion Laboratory working first on the guidance and control of the Galileo spacecraft, and since 1983 performing research in robotics at JPL. He has published numerous conference and journal papers and holds two US patents related to robotics control. His pioneering work in robot calibration was used to develop techniques to utilize manipulators as an aid in brain neurosurgery at the Long Beach Memorial Hospital in California in 1986.*