IAC-07-D3.4/D3.5/E5.5.02

# Managing Space Technology Development at NASA

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**ABSTRACT**

NASA uses a structured process for managing projects that develop advanced space technologies and transition them into the designs of flight systems. The four-part process consists of formulation, approval, implementation, and transition. In the formulation phase, technology needs are derived from mission concept studies, various technical approaches for meeting the technology needs are identified, technical performance goals called Key Performance Parameters (KPPs) are established, and a project plan is developed. Prior to project approval, an Independent Formulation Review is conducted to ensure that the project objectives are aligned with the mission needs, and that the project is well planned to meet the objectives. In the implementation phase, the technology development project matures the technology, and progress towards the KPPs is evaluated in periodic status reviews. Technology Readiness Levels (TRLs) are used throughout the project lifecycle to assess the progress of technology maturation. In the transition phase, technologies that are successful in achieving the required level of maturity are transitioned to a customer for further development, are used in system designs, or are thoroughly documented for resumption of development at a later date. The customer or end-user of the technology is involved in all phases of the technology development process.

**FULL TEXT**

## Introduction

As part of a global exploration strategy to extend human presence beyond Earth, NASA is planning to establish an outpost on the Moon around 2020. To accomplish this ambitious goal, new technologies will be needed to enable the lunar exploration architecture, reduce mission risk and costs, and make the outpost sustainable.

In the past, NASA invested in a broad range of low-maturity, crosscutting technologies that were not directly tied to a specific mission need in the hope that a few innovative concepts would eventually find their way into future missions. This approach would not be effective for the exploration program because the maximum benefit from limited technology investments must be obtained to meet the program's cost and schedule constraints. A focused technology development process is needed to ensure that mature technologies meeting specific performance requirements are delivered on time to be inserted into the design of flight systems.

In 2005, NASA established the Exploration Technology Development Program (ETDP) to provide mission enabling technologies to the Constellation Systems Program, which is designing the flight systems for lunar exploration. The ETDP uses a structured management process to identify technology needs and set priorities, formulate project plans, assess technology maturity and track progress during development, and transition technology products to customers or end-users.

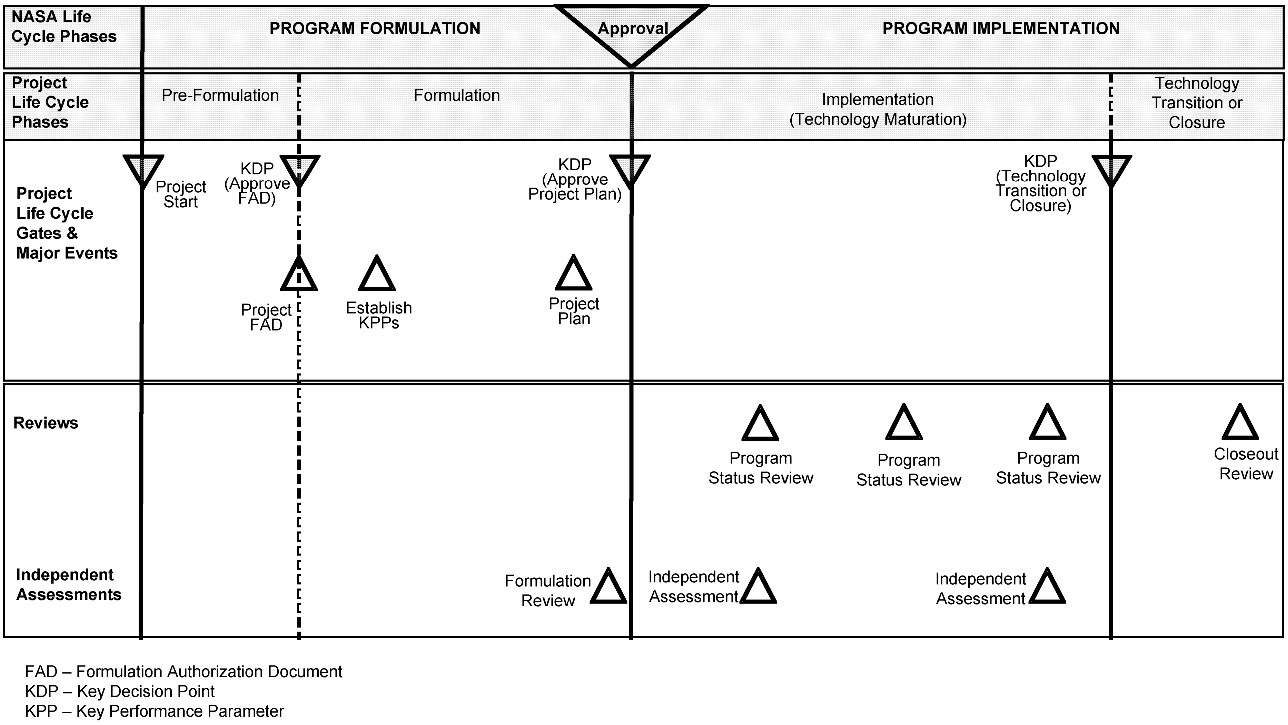


Fig. 1: Technology Project Life Cycle (Ref. 1).

## Technology Project Life Cycle

A technology program such as the ETDP consists of several focused technology development projects. Each project matures a particular technology or a set of related technologies to the point where it is ready for use by a customer. Customers are the intended end-user for the technology products being developed, and they are involved throughout the technology development process in setting requirements, assessing technology maturity, and transitioning technologies into mission designs. Typically, a customer is a space flight project or other focused technology development project where further development occurs to meet a specific mission requirement. The primary customer of the ETDP is the Constellation Systems Program.

New technologies often emerge from fundamental research where basic scientific principles are investigated, and concepts for their application are formulated. The early stages of technology development are usually performed in the laboratory; later stages may involve field tests or flight demonstration experiments to validate the technology in relevant environments.

NASA has established common management practices for its technology development programs and projects (Ref. 1). The management process uses detailed project plans, formal reviews, and Key Decision Points (KDPs) to guide technology projects through their life cycle. A KDP occurs when the program manager determines the readiness of a project to progress to the next phase of its life cycle. As such, KDPs serve as gates through which projects must pass. To support the decision process, a KDP is typically preceded by one or more reviews.

The life cycle of a typical focused technology development project consists of four phases: formulation, approval, implementation, and transition (Fig. 1).

In the formulation phase, technology needs are derived from mission concept studies, various technical approaches for meeting the technology needs are identified, technical performance goals called Key Performance Parameters (KPPs) are established, and a project plan is developed.

Prior to the project approval KDP, a Formulation Review is conducted by independent reviewers to ensure that the project objectives are aligned with the mission needs, and that the project is well planned to meet the objectives.

In the implementation phase, the technology development project matures the technology, and progress towards the KPPs is evaluated in annual Program Status Reviews. At these reviews, independent reviewers may recommend to the program manager that the project be continued, revised, or discontinued. Technology Readiness Levels (TRLs) are used throughout the project lifecycle to assess the progress of technology maturation (Ref. 2).

In the transition phase, technologies that are successful in achieving the required level of maturity are transitioned to a customer for further development, are used in system designs, or are thoroughly documented for resumption of development at a later date.

## Project Formulation

The formulation of a technology development project involves defining the customers, identifying technology needs, evaluating alternatives, establishing KPPs, and planning project implementation.

In the pre-formulation phase, technology needs are identified through systems analysis and mission architecture studies. In 2005, NASA conducted the Exploration Systems Architecture Study (ESAS) to define the reference architecture for lunar exploration missions (Ref. 3). The ESAS also determined the priorities for technology development to support the reference architecture. Exploration technology needs are continuing to be refined by the Lunar Architecture Team (LAT), which is developing plans for the lunar outpost (Ref. 4).

Twenty-one focused technology projects were formulated in the ETDP to address the technology priorities resulting from the ESAS and LAT activities (Ref. 4). These projects are led by the NASA field centers, and they encompass major technical disciplines such as power, propulsion, avionics and software, structures and materials, robotics, life support, and in-situ resource utilization (Ref. 5).

Project formulation begins with the preparation of a Formulation Authorization Document (FAD). The FAD describes the goals and objectives of the new project, the scope of work to be accomplished, and the cost and schedule constraints. The FAD also designates the project manager and major participants. Approval of the FAD by the program manager authorizes the project to move from the pre-formulation phase to the formulation phase, in which KPPs and detailed project plans are developed.

## Key Performance Parameters

To increase the likelihood of successful technology infusion, technology projects define KPPs that are important to the customers. KPPs consist of measurable engineering parameters that would be readily understood and used by engineers concerned with the ultimate application of the technology. For example, the KPPs for an advanced lithium-ion battery might be the required specific energy (Wh/kg) and operating temperature (Table 1).

| KPP | State-of-the-Art | Threshold | Goal |
|---|---|---|---|
| Specific Energy | 90 Wh/kg | 120 Wh/kg | 140 Wh/kg |
| Operating Temperature | -20 $^{o}$C to +40 $^{o}$C | -40 $^{o}$C to +40 $^{o}$C | -60 $^{o}$C to +60 $^{o}$C |

Table 1: Key Performance Parameters for an Advanced Lithium-Ion Battery.

For each KPP, both a goal and a threshold are specified. The goal is a performance level that the project team is striving to achieve, and the threshold is the minimum performance level that users agree is acceptable. Typically the threshold KPP values are set beyond the current state-of-the art to warrant investment in the project. KPPs include information that enables an assessment of technology maturity throughout the development process. The definition of a KPP includes defining the appropriate environment and the component, subsystem, or system within which the KPP measurements are to be made. KPPs are reviewed annually by the customer to verify that they are still aligned with mission requirements.

## Project Plan

The development of a detailed project plan is required before the project can proceed from the formulation phase into the implementation phase. The project plan documents the baseline cost, schedule, and technical performance goals, and is used for tracking progress during implementation. The essential elements that it contains are:

- the overall objectives of the project, the technology needs to be addressed, and a description of the technology products to be developed;
- the technical approach for technology development and validation;
- the Key Performance Parameters;
- the management approach, and identification of participating organizations and the project's customers;
- the annual funding requirements for each project task, and other resource requirements such as personnel and test facilities;
- the integrated master schedule that includes all project tasks, major milestones, reviews, and decision points;
- the work breakdown structure that divides the project into manageable pieces of work to facilitate planning and control of cost, schedule, and technical content;
- the risk management approach for identifying and mitigating major project risks;
- the technology transition strategy for ensuring that the technology products will be used by the project's customers;
- and the plans for periodic independent assessments and status reviews that will be used to evaluate the project's progress and technical quality.

The project plan is an agreement between the project manager, who prepares it, and the program manager, who approves it. The project plan may be revised as necessary if the technology needs change, unanticipated technical or managerial problems occur during implementation, or the required resources are not available.

**Project Implementation**

The implementation of a technology development project involves laboratory research and analysis to advance the technology towards the KPPs, field tests or flight demonstration experiments to validate component technologies in representative systems operating in relevant environments, annual Program Status Reviews to evaluate technical progress, and assessment of technology maturity using Technology Readiness Levels.

If the laboratory research begins with a basic concept for a new technology that has not been proven to be feasible, multiple technical approaches may be pursued in parallel to reduce risk. The most promising approach is down selected for further development at a Key Decision Point in the project's schedule.

As the technology project proceeds, its progress relative to the baseline project plan is assessed in annual Program Status Reviews. The customers are involved in the Program Status Reviews to ensure that the technology being developed is still relevant to their needs, and to determine the current TRL, which depends on the intended application of the technology.

In addition to the annual Program Status Reviews, the project may be periodically peer reviewed for technical quality by an external organization such as the National Research Council. These Independent Assessments (IA) provide feedback that is not biased by internal institutional concerns to the program manager and the stakeholders who fund the program.

Projects are required to submit monthly reports of accomplishments, issues, cost and schedule performance, and plans for the next month to the program manager.

**Earned Value Management**

Earned Value Management (EVM) is a rigorous program control method that NASA uses to increase the likelihood that the project will be successful in achieving its technical objectives within cost and schedule constraints (Ref. 6).

EVM uses a baseline plan for assessing technical, cost, and schedule performance. The baseline plan consists of a Work Breakdown Structure (WBS), a project schedule with milestones for each element in the WBS, and an allocation of the project's available resources necessary to achieve each milestone. The milestones should be chosen at intervals sufficient to demonstrate steady progress towards achieving the overall KPPs for the project.

As work is performed, the project earns value when milestones are achieved. The actual cost and schedule required to achieve each milestone are compared to the budgeted cost and schedule for the milestone that were established in the baseline plan. EVM cost and schedule performance metrics are reported monthly for each major WBS element.

Although technology development is often difficult to plan, especially for exploratory research, EVM can still be a useful management tool. It can help the project manager identify problem areas within the WBS as they arise so that corrective action can be taken to get the project back on plan. At a higher level, EVM also gives the program manager insight into the overall health of the project.

**Technology Maturity Assessment**

Accurate assessment of technology maturity is critical to technology advancement and its subsequent incorporation into operational systems. Trying to apply immature technologies has led to technical, schedule, and cost problems during systems development.

NASA uses the TRL scale, which ranges from 1 to 9, for indicating the current state of maturity of a particular technology, and its readiness for application in a flight system. The definitions of each TRL are given in Table 2.

Major U. S. government acquisition programs are now required to certify that Critical Technology Elements have been demonstrated in a relevant environment (TRL 6) at program initiation. A technology element is “critical” if the system being acquired depends on this technology element to meet operational requirements with acceptable development cost and schedule, or if the technology element or its application is new or novel (Ref. 7).

TRLs by themselves are insufficient for assessing technology maturity. TRLs must be used in conjunction with the KPPs, which establish measurable goals for technology development. TRLs depend on the KPPs. For example, a quantum dot solar cell with a KPP of 50 percent conversion efficiency may have a TRL of 2, while a multi-junction solar cell with a KPP of 30 percent efficiency may have a TRL of 5.

| TRL | Definition |
|---|---|
| 1 | Basic principles observed and reported. |
| 2 | Technology concept and/or application formulated. |
| 3 | Analytical and experimental critical function and/or characteristic proof of concept. |
| 4 | Component and/or breadboard validation in laboratory environment. |
| 5 | Component and/or breadboard validation in relevant environment. |
| 6 | System/subsystem model or prototype demonstration in an operational environment. |
| 7 | System prototype demonstration in an operational environment. |
| 8 | Actual system completed and "flight qualified" through test and demonstration. |
| 9 | Actual system flight proven through successful mission operations. |

Table 2: Technology Readiness Levels (Ref. 2)

TRLs also depend on the mission application of a particular technology. For example, the Ares launch vehicles being developed for lunar exploration missions will use a 5-segment Solid Rocket Booster (SRB) that is derived from the 4-segment SRBs used on the Space Shuttle to minimize development costs. Since the Ares SRB has a different configuration and mission application, its TRL is 5, while the Shuttle SRB is TRL 9.

The TRL of an overall system is determined by the subsystem or component having the lowest TRL in the system.

TRLs and KPPs are used throughout the project lifecycle to assess technology maturity. An independent group that includes the customers should validate the current state of maturity. The initial maturity assessment is done in the Formulation phase, and updated annually at the Program Status Reviews. At the conclusion of the project, an independent assessment of the final TRL is performed.

**Technology Transition**

When a technology has reached the required level of maturity, it is transitioned to the customer for further development, or incorporated into system designs. Transition occurs when the customer assumes management and financial responsibility for technology development. The transition is not tied to a specific TRL. In this phase, the investigations may also be discontinued.

At the conclusion of a technology project, a Closeout Review of the project's accomplishments is held, an independent assessment of the final TRL is performed, and the data resulting from the project are documented in a final report.

Often technologies do not make this transition successfully, either because the technology needs that were identified at the start of development have changed, or the customer perceives the technology as having too high risk for use in a mission.

To increase the likelihood that technologies are successfully transitioned to customers, formal agreements can be made between the technology supplier and the customer at the start of the technology project. These Customer Supplier Agreements (CSAs) document the technology needs and performance requirements, the technology products that will be delivered, and the schedule for delivery. The agreements are signed by the technology project manager and the intended customer. The CSAs insure that the technology supplier has a clear understanding of the customer's needs, and that the customer is committed to using the technology being developed by the supplier. CSAs are reviewed by both parties annually to insure that they are still valid, and revised if necessary.

**Field Demonstrations**

To reduce the risk for future operations on the lunar surface, the Exploration Technology Development Program conducts field demonstrations of new technologies every year. These demonstrations involve humans and robotic systems working together to perform representative exploration and lunar outpost assembly tasks. They are performed in remote locations that are analogs of the lunar surface environment. Field tests have been conducted at Meteor Crater in Arizona, at Haughton Crater on Devon Island, Canada, at McMurdo Station in the Antarctic, and in the NASA Extreme Environment Mission Operations (NEEMO) underwater habitat off the coast of Florida (Fig. 2).


Fig. 2: Desert Research and Technology Studies (Desert RATS) field test near Meteor Crater, Arizona (Ref. 8)

Field demonstrations are key for enabling successful technology development and transition for several reasons: they establish a path for technology infusion into the Constellation Systems Program by focusing technology development projects on specific deliverables that are validated in representative system applications; they prove out operational concepts to inform future exploration architecture studies and requirements development; and they grow capability in small affordable steps by adding technology improvements every year.

**Conclusion**

NASA uses a rigorous process to manage the development of advanced space technology for future lunar exploration missions. Detailed project plans, Key Performance Parameters, technology readiness assessments, Earned Value Management, Customer Supplier Agreements, and field demonstrations insure that technology development projects are well aligned with mission needs, that progress is measured, and that technology products will be successfully transitioned to end-users. The Exploration Technology Development Program is leading the way in developing and implementing these innovative management practices.

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