OFFICE OF THE DIRECTOR
DEFENSE RESEARCH AND ENGINEERING
SYSTEMS ENGINEERING

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Systems Engineering During the Materiel Solution Analysis and Technology Development Phases

1 Introduction

Systems engineering provides the technical foundation for an acquisition program throughout the acquisition process. Particularly in the early stages of an acquisition, systems engineering analysis and products are vital to the early program office.[1] During this time, the program seeks to assess the feasibility of addressing user needs and the technology of potential solutions, and it determines robust estimates of cost, schedule, and risk intended to result in a predictable, disciplined acquisition. This paper describes actions of government and developer systems engineering teams during the pre-Milestone B phases of Materiel Solution Analysis (MSA) and Technology Development (TD).

2 Role of Systems Engineering in Materiel Solution Analysis

Figure 2-1 depicts the key systems activities, products, and reviews during the first phase of acquisition, MSA, which follows the Materiel Development Decision (MDD) and extends through Milestone A. During the MSA phase, the program identifies one or more materiel solutions to address user capability gaps, based on an Analysis of Alternatives (AoA) conducted by an organization independent from the program office. The AoA is essentially a trade study addressing user needs and solution options. "The purpose of the AoA is to assess the potential materiel solutions to satisfy the capability need documented in the approved ICD" (DoDI 5000.02, p.15).

During MSA, systems engineering plays a role in two ways. First, engineering considerations should be a component of the AoA guidance and should be addressed in the study plan. The program office should provide input to the AoA and observe AoA progress. Without these considerations, approaches could be selected that include technical risk not recognized in the analysis.

[1] The terms "program," "program office," and "program manager" are used throughout this paper to refer to the organizations and positions established to support these early acquisition phases, recognizing that a program of record is not formally established until Milestone B.

Second, the AoA is conducted independently from the early program office and forms the basis for selecting the recommended approach(es) for materiel solution(s). At the close of the AoA, the program office takes ownership of the approach and conducts additional engineering analysis to support the development of the Technical Development Strategy (TDS), the Test and Evaluation Strategy (TES), and the Systems Engineering Plan (SEP).

It is critical that the program office's systems engineering analysis build upon the AoA results and provide the program manager with the technical basis for executing the TD phase, including risk-reduction efforts. In particular, during MSA the systems engineering team performs the following activities:

- Confirm the Concept of Operations (CONOPS) and develop mission and functional threads with users
- Develop initial view of system requirements and system design concepts
- Identify critical technology elements (CTEs)
- Determine external interfaces and interoperability
- Identify critical program information (CPI)

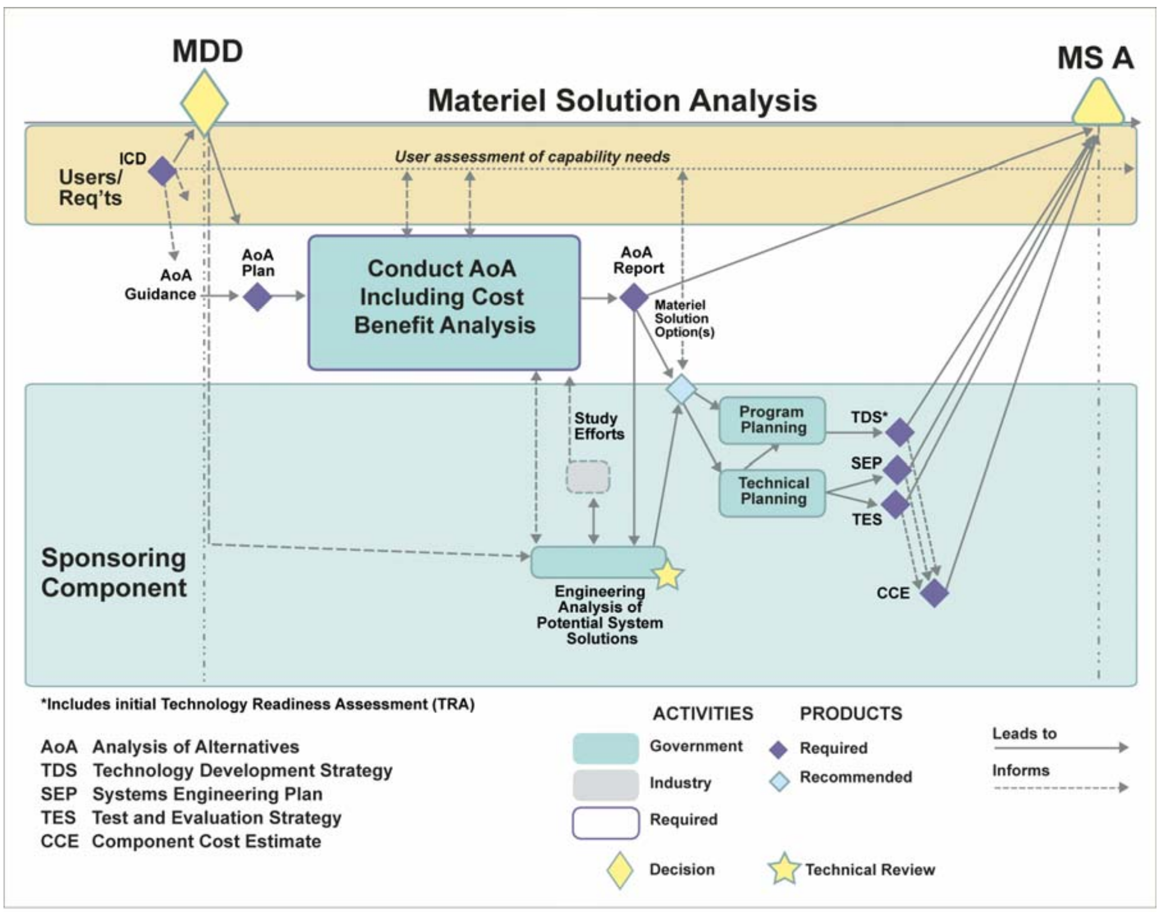

Figure 2-1 Systems Engineering Activities, Products, and Activities in Materiel Solution Analysis

2.1 Confirm Concept of Operations and Develop Mission and Functional Threads with Users

During the MSA and subsequent phases, it is critical that the program office work closely with the users to identify and evaluate options for filling capability gap(s). Technical feasibility and affordability should inform user requirements. Reciprocally, user needs must inform technical trades. Beginning with engineering analysis and the definition of system requirements, the user CONOPS and mission threads must provide a strong foundation, and the program must maintain a working relationship with users to achieve a balance between user requirements (eventually documented in the Capabilities Development Document [CDD] at Milestone B) and technical feasibility.

2.2 Develop Initial View of System Requirements and System Design Concepts

Once the proposed materiel solution(s) are determined, the systems engineering team begins its engineering analysis, which could include conducting trade studies and formulating possible system solutions. The analysis results in preliminary system functional and performance requirements and possible overall design options. This early technical work is critical as it provides the program manager with the needed engineering basis for the initial view of the system acquisition, requirements, technology, and development considerations and risks. It also provides essential information on test and evaluation issues, support and maintenance objectives, work scope, and cost and schedule drivers. All of these factors affect the acquisition approach and are addressed in the TDS for the TD phase.

2.3 Identify Critical Technology Elements

The engineering analysis of potential materiel options includes identifying potential hardware and software options required for implementation. Application of functional threads is one approach. The program team, as part of its system solutions analysis, conducts a technology maturity assessment of the hardware and software options with a focus on the CTEs. The team conducts the initial Technology Readiness Assessment (TRA) during MSA and reports it in the TDS. The identified CTEs become one basis for risk reduction/prototype efforts represented in the TDS, identified in the TES, and executed during the TD phase.

2.4 Determine External Interfaces and Interoperability

Because new acquisitions are intended to support user capabilities in a networked environment, the program team needs to understand the context in which the potential systems will be employed (based on CONOPS and mission/functional threads) and how this context affects the system acquisition, including programmatic and technical interfaces and interdependencies. A systems engineering focus on the system of systems (SoS) context, including external interfaces and interoperability, facilitates an understanding of end-to-end system performance and its implication for the CDD. It also identifies changes in other systems or dependencies needed to address the capability gap.

2.5 Identify Critical Program Information

It is imperative that the program identify CPI in the initial stages of systems engineering so the impact of CPI on possible system solutions and requirements can be addressed early and not compel a system redesign after substantial investment has been made. The program's CPI will be documented in the TDS. As shown in Figure 2-2, the results of the MSA systems engineering analysis provide critical technical information to the planning for the TD phase. For example, the team uses the analysis to determine the plan for CTE risk reduction, prototyping, and competing preliminary designs, including scope, objective, and who performs different activities (industry or government). This technical planning is an essential element of the TDS and is the program's initial acquisition strategy. The technical plan includes the work content for the TD phase, against which cost and POM estimates are prepared. The program uses technical planning results to develop the TD plan and RFPs, which are documented at Milestone A in the DoDI 5000.02–required SEP, TDS, and TES.

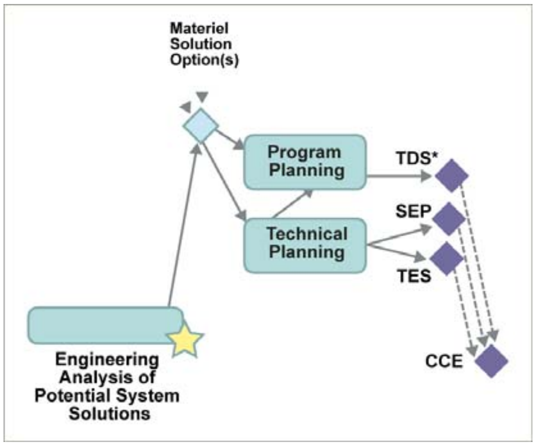

Figure 2-2 Effect of Proposed Materiel Solution on Milestone A Program Documents

3 ROLE OF SYSTEMS ENGINEERING IN THE TECHNOLOGY DEVELOPMENT PHASE

The TD phase incorporates the objectives of buying down technical risk and developing a sufficient understanding of possible solutions to make a sound decision about initiating a formal acquisition program. Thus there are two types of activities in TD: maturing technology through CTE risk reduction and competitive prototyping, and initial end item design (through preliminary design).

Figure 3-1 depicts the key activities, products, and reviews during this second phase of an acquisition life cycle, from Milestone A through Milestone B. The activities in this figure reflect the full set of possible TD phase activities. Eliminating or tailoring of these elements is specific to the system solution(s) as determined by the MSA analysis and represented in the TDS. Tailoring the TD phase is discussed in Section 4.

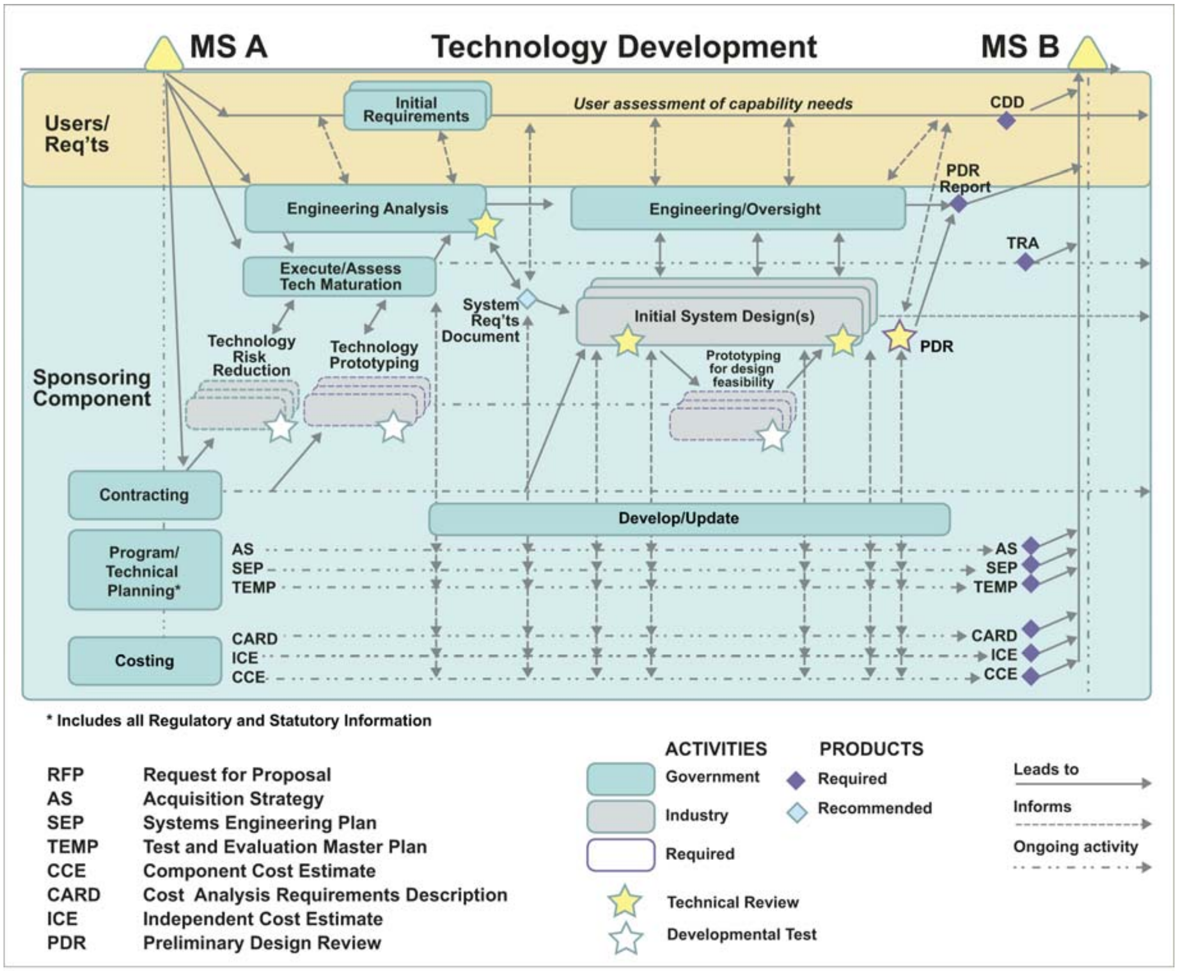

Figure 3-1 Systems Engineering Activities, Products, and Activities in Technology Development

The TD phase addresses a set of critical activities leading to the decision to establish a program of record. The systems engineering activities, including test and evaluation, provide the technical foundation for this decision. Depending on the nature of the technology development strategy, the order and characteristics of these activities may change. As Figure 3-1 shows, the series of technical and program planning actions during TD are informed by the results of the technical activities conducted during this phase. These activities include

- Technology maturation
- End item design

3.1 Risk Reduction

A key element of systems engineering during technology development is to mature the critical technologies either through CTE demonstrations or prototyping needed for a particular system solution.

The program office team provides technical management and may employ industry, government laboratories, the Service science and technology (S&T) community, or Federally Funded Research and Development Centers (FFRDCs)/universities to accomplish specific risk-reduction or prototype tasks as described in the SEP. These tasks were identified in the TDS and spelled out in the RFPs/task orders prepared either in the MSA phase or post Milestone A. The program office team completes an assessment of technology maturation results and their impact on the requirements and specific system solutions.

3.1.1 Technology Maturation

During the MSA phase, the program analyzed a number of system solutions and identified technology risks, including technologies requiring further maturation before acceptance as implementable components within a solution. Technology maturation involves design, development, and testing. There could be one or more risk areas related to hardware, software, or IT, and there may be multiple industry contracts/government efforts for maturing the technology. The TES should stipulate the test and evaluation approach, assessing the results of the technology maturation activities.

3.1.2 Technology Competitive Prototyping

Prototyping broadens the opportunity for technology maturation by engaging multiple parties to compete for technology prototypes. Prototyping can help identify the nature of risk at the subsystem/system level (functionality, performance, or affordability) and may be used to encourage competition. As with a technology maturation effort, this activity should be identified in the TDS, specified in RFPs/Task Orders, technically managed by the project office as described in the SEP, and included in the TES with specific test objectives. There may be competing prototypes for inclusion in a system solution or competing system solution prototypes. Industry is the usual participant in prototyping, but government laboratories, S&T communities, and FFRDCs/universities also conduct some prototyping.

3.2 End Item Design

For systems with significant implementation uncertainty, the program initiates development of the required end item system during the TD phase and continues until the team has defined an allocated baseline and preliminary design. The program uses the knowledge gained in this initial design activity to refine the estimated cost, schedule, and performance that can be achieved to meet the user capability needs. This initial design activity includes setting system requirements informed by the CDD, decomposing requirements, establishing the functional architecture, defining the functional baseline, determining the physical architecture, and allocating functionality and performance to the physical elements, thereby defining the allocated baseline (preliminary design). This effort may be performed by multiple contractor design teams depending on the program's acquisition strategy. To support the demonstration of design feasibility, these design activities may be supported with design prototypes.

3.2.1 Engineering Analysis

The program office team executes the TD phase plan as described in the TDS, TES, and SEP. The primary systems engineering objective is to gain sufficient technical knowledge to develop the program's System Requirements Document (SRD) and to verify that the required technology for the system solution(s) is sufficiently mature (Technology Readiness Level 6 or higher) before proceeding into an end item design or Milestone B. The program office systems engineers use the results from engineering activities, such as CTE risk reduction and prototyping, to refine system requirements.

Concurrently, the program office team constructs a technical baseline based on a system solution that satisfies the CDD, or informs the CDD developers regarding what is technically achievable within the envisioned constraints of budget, fielding date, and technology maturity. This system solution is not a prescription for an ultimate system solution. Rather, it provides a technical foundation for refining system requirements, program cost realism, and TEMP development, and it builds the government technical expertise for follow-on TD and Engineering and Manufacturing Development (EMD) phase activities such as RFP/source selection for competing preliminary design contracts. This activity is completed with a successful System Requirements Review (SRR), a recommended technical review.

This technical baseline is incorporated into the Cost Analysis Requirement Description (CARD) to develop program cost estimates, and it provides a technical foundation for the EMD phase Acquisition Program Baseline (APB). The program office team participates in internal and external technical reviews, identified in the TDS and described in the SEP.

3.2.2 System Requirements Document

The program office team defines system-level functional and performance requirements derived from items such as the CONOPS, system-level performance metrics, mission threads/use cases, and usage environment, which are captured in a program's SRD. The system requirements should be based on a system solution defined at the system and subsystem level and supported by CTE and prototyping results. The contractor uses these system requirements to develop the system-specification and functional and performance requirements necessary to conduct initial end item design.

3.2.3 Engineering Oversight

When it awards end item design contracts, the program office team, working as an integrated process team with representation from functional areas across the program, commences oversight of the performing contractors. The team's focus is on the technical products and underlying engineering work that the contractor is obligated to provide. For award fee contracts, the team's understanding and knowledge provide important information on which to base periodic award fee determinations and to shape subsequent contractor performance. The program office team continues its engineering function, using the contractors' provided information to further refine the technical baseline, inform the CDD on technical reality, and update the TEMP, TRA, and CARD inputs.

For two or more competing contractors, the program office team must ensure each contractor's proprietary rights are maintained throughout execution of the engineering oversight role. As one aspect of a typical program office–contractor relationship, the government seeks an in-depth understanding of what is or is not progressing well within the contract or what may be an emerging problem that requires attention.

An updated SEP coming out of the engineering analysis effort should describe the program office team's oversight and insight roles. The team must evaluate the emerging initial designs and ensure that the preliminary design information is incorporated into the planning for EMD. This evaluation may include modifications to program documents such as the CDD, cost estimate, acquisition strategy, APB, SEP, and TEMP. (The value of competing a preliminary design before Milestone B is realized only if the Preliminary Design Review [PDR] results inform the planning for EMD.)

3.2.4 Competing Design Efforts

Competing contractors execute their technical approach as contained in the proposed Integrated Master Plan (IMP) and Integrated Master Schedule (IMS), or similarly produced plan and schedule products that were part of the proposal and subsequently placed under contract. Contractors decompose the SRD first into a system specification and ultimately into lower-level subsystem and component specifications. The contractor teams usually perform a number of trade studies and component design/test efforts to better understand and define these specifications. The contractor teams then establish the linkage from the SRD to system specifications, functional and performance requirements, and their allocation to subsystems and possibly lower-level components.

The IMP establishes key contract milestones and associated criteria, which are associated chronologically in the IMS with their necessary interdependencies. Major technical milestones include the SRR, System Functional Requirements (SFR), and the PDRs. The program may hold a series of PDRs for individual configuration items in preparation for a system-level PDR. The government SEP and the contractors' Systems Engineering Master Plan (SEMP) shape the governance and conduct of these reviews, including action items and issue resolutions. Contractor and program office configuration management (CM) are established for the functional and allocated baselines, including the contractor's specification tree elements.

Throughout the TD phase, the program office team works with the users to ensure that the results of the technical work are considered in development of the CDD. Other program office Integrated Product Teams (IPTs) are informed by the systems engineering team technical work as well as by other programmatic activities requiring a program manager decision or opinion. Throughout TD, technical results, culminating with the PDR, provide robust technical information supporting the key Milestone B documents (Figure 3-2) delivered at Milestone B and forming the basis for the formation of a program of record. When the PDR is conducted before Milestone B, the results of the preliminary design process can provide the technical foundation for key milestone documents and decisions.

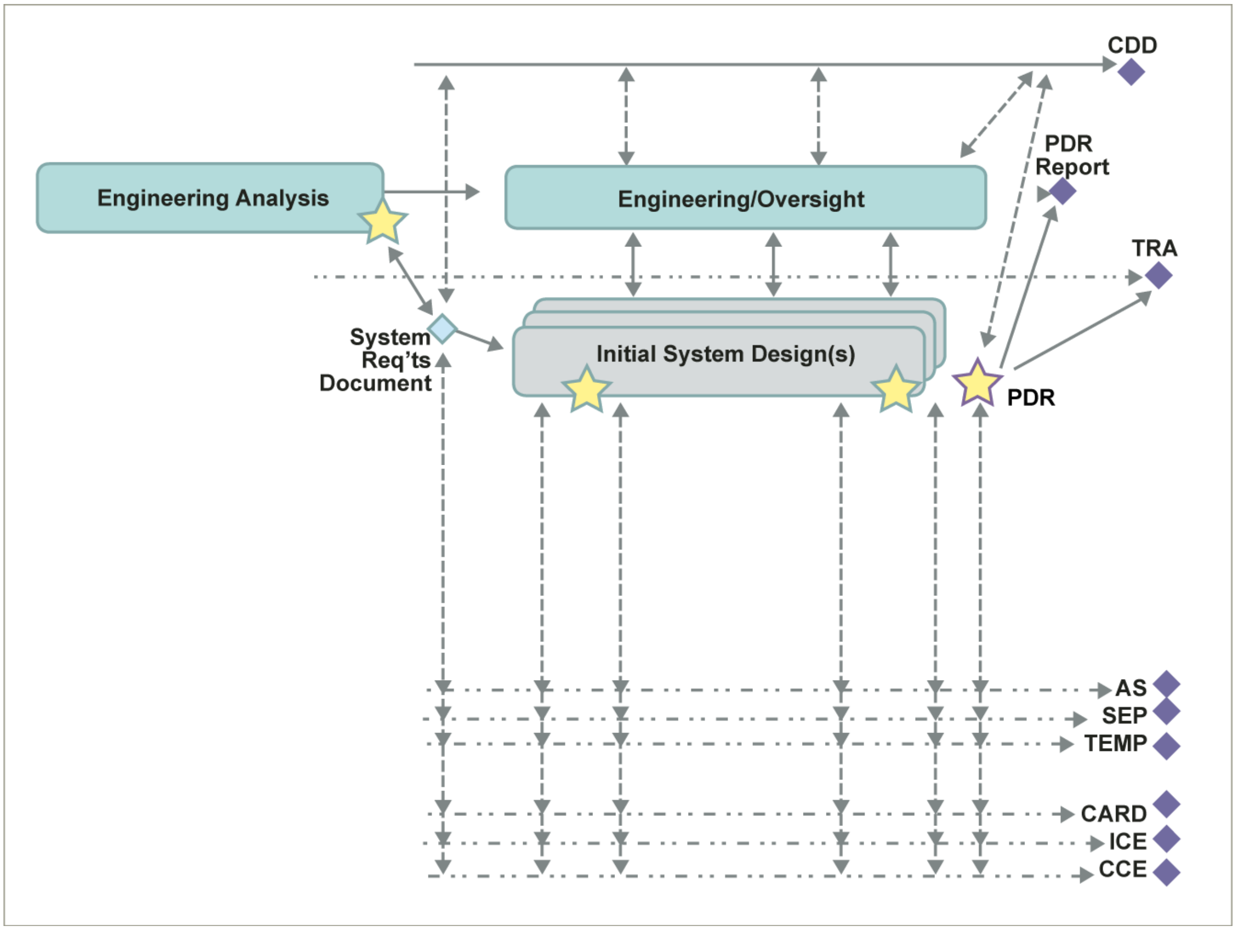

Figure 3-2 Effect of Pre-Milestone B PDR on Program Technical Foundation

4 SYSTEMS ENGINEERING ANALYSIS TO SUPPORT TAILORING TECHNOLOGY DEVELOPMENT

To illustrate the type of decisions the program manager will face in creating the TDS, Figure 4-1 outlines a series of notional decision paths forward. These notional paths illustrate the type of technical information and planning needed for the SEP, TES, and TDS. In any specific program circumstances, there may be variants or combinations of these paths.

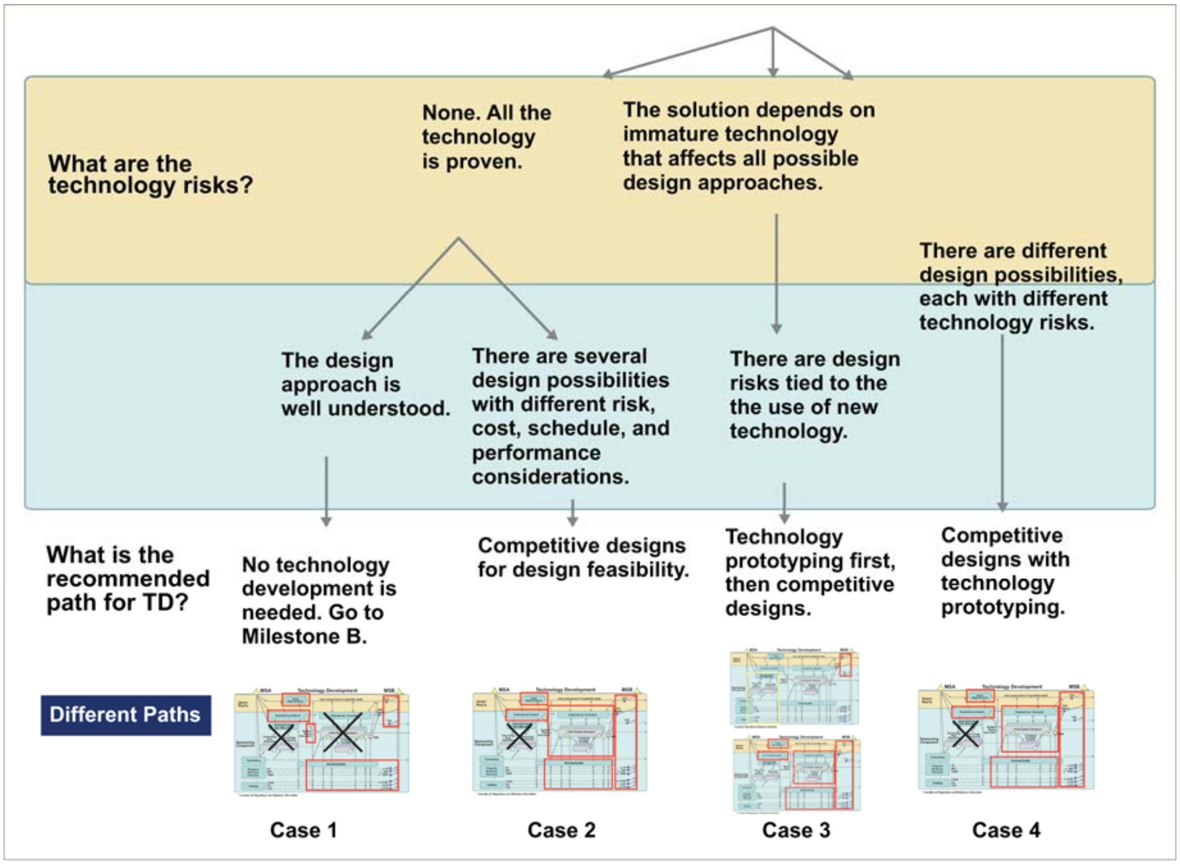

Figure 4-1 Notional Situations Facing Program Managers Preparing a Technology Development Strategy

Selection of the technical development path forward to Milestone B is a continuum of potential paths rooted in the technical risk or opportunity gain that a program can accept at Milestone B. The MSA engineering analysis is used to determine the placement of a solution in this continuum. The MSA technical planning then lays out the technical development effort required to achieve the desired risk reduction/opportunity gain levels for Milestone B.

The specific path's programmatic and technical information is contained in the TDS, SEP, TES, and the TD phase RFPs. These documents contain the critical technical and programmatic information required for successful execution of the TD phase. When conducted correctly, the program reduces execution risk and affords informed decision making.

In Case 1 (Figure 4-2), the program includes mature technology and an understood implementation. In this case the focus would be on the technical work necessary to prepare for the Milestone B decision (technical work indicated by red boxes). In particular, the program would focus on developing the system requirements and engineering analysis necessary for the development of critical program definition with respect to anticipated cost, schedule, and performance.

For this case, the technical level of risk is acceptable for proceeding directly from engineering analysis to Milestone B without the need for competing preliminary design efforts. The SE team will complete an SRD and updated SEP. The team should use caution in coming to this conclusion as recent experience shows that programs have often sought to bypass technology development and progress directly to design and development. Subsequently identifying technology and other risks following the program decision at Milestone B, when there is limited recourse to address these risks, puts the program at risk. The Milestone Decision Authority (MDA) would determine if the program should proceed to Milestone B based on the results of the AoA and supporting engineering analyses.

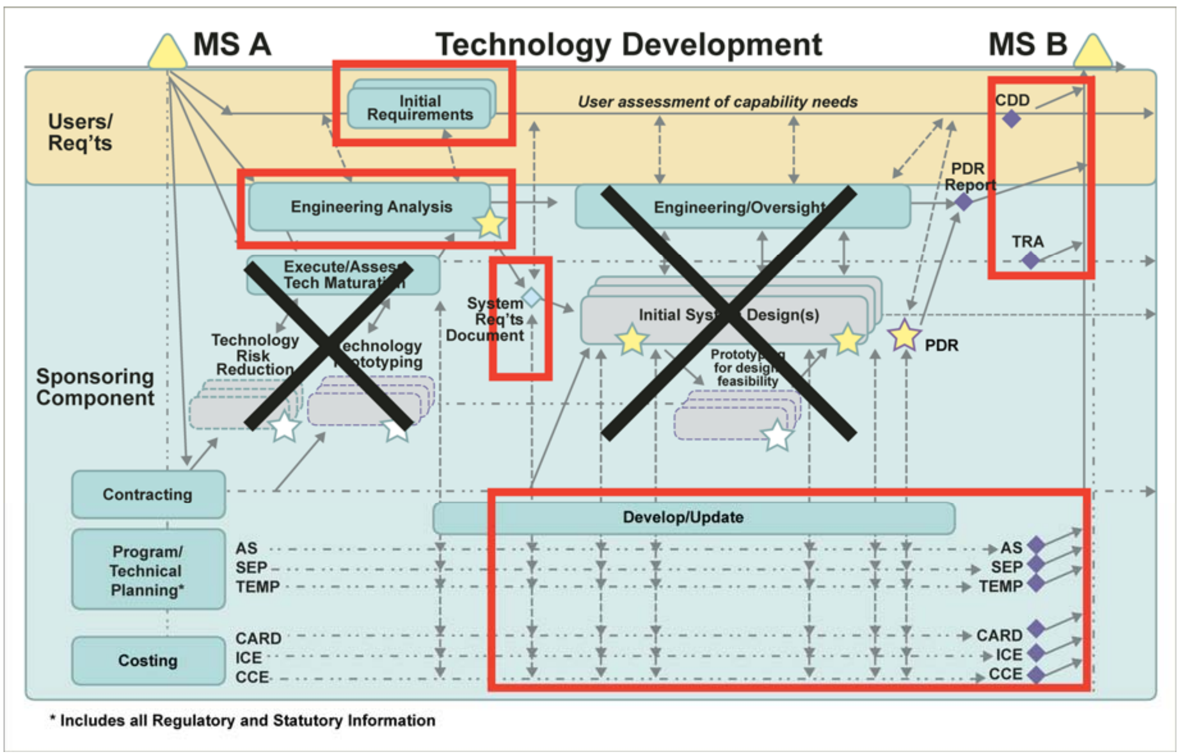

Figure 4-2 Case 1: Mature Technology and Understood Implementation

In Case 2 (Figure 4-3) with mature technology but design uncertainty, the prototyping emphasizes design risk (i.e., integration, manufacturing). In this case, the program needs to reduce design uncertainty before making a program commitment. The program office team develops the SRD, updates the SEP, and provides input to the RFP for competing preliminary design contracts. During the competing preliminary design efforts, the manufacturing risk "burn down" occurs.

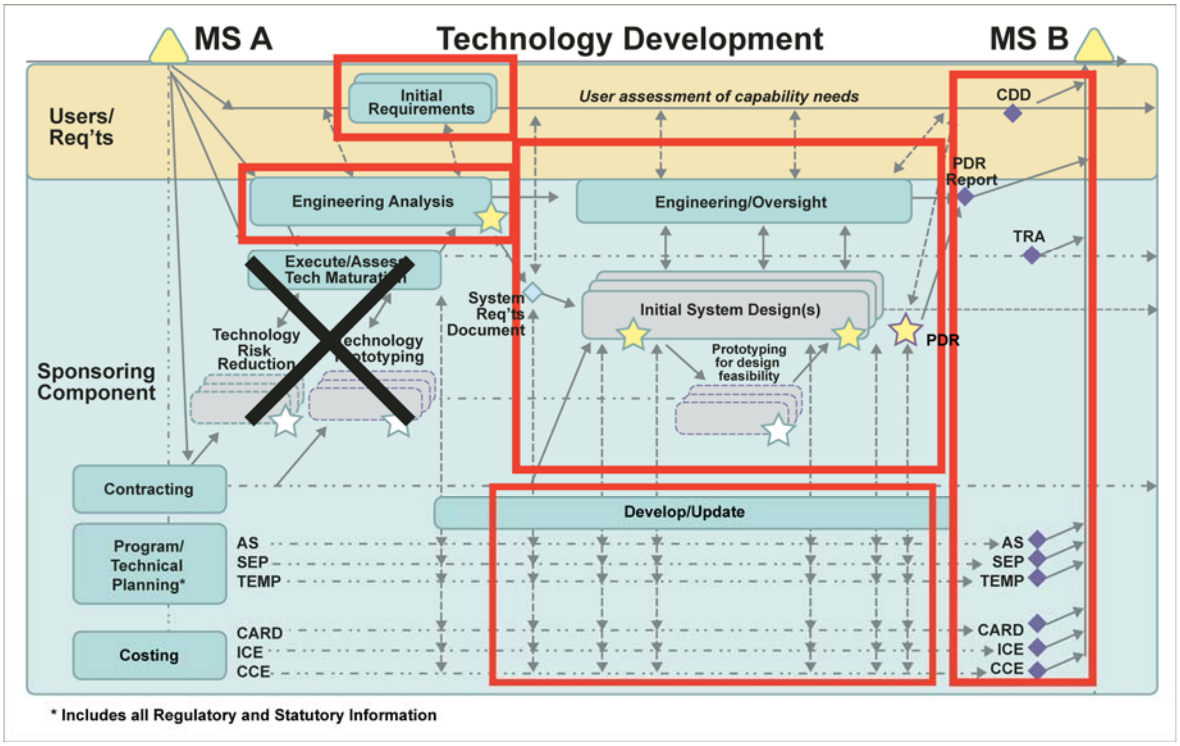

Figure 4-3 Case 2: Mature Technology with Uncertain Design

In Case 3 (Figures 4-4 and 4-5), technology needs to be matured before any design work begins. In this case, a two-step sequential strategy would be advised. The first step would be technology development work to address key cross-cutting technology needs and a set of competing designs to address implementation risk before making the Milestone B business decision. Step 1 (Figure 4-4) addresses the common critical technology issues with a key decision based on technology maturity, including CTE prototyping (yellow box).

If technology maturity can be achieved as determined by technical reviews and the TES criteria, then Step 2 (Figure 4-5, red boxes) addresses design uncertainty with competing preliminary designs prior to making a program commitment at Milestone B. Through engineering analysis, the program team develops the SRD and provides input to the RFP for the competing preliminary design contracts. The results of the design work, which may also be supported by prototyping to demonstrate implementation feasibility of the design(s), provide significant engineering-based information for the Milestone B decision.

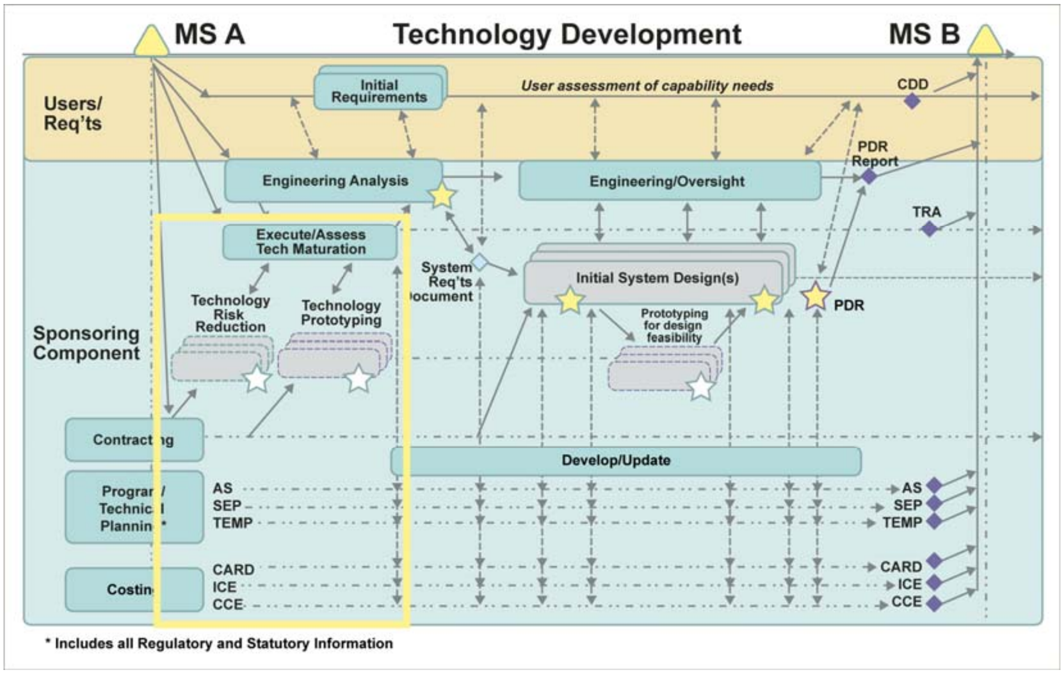

Figure 4-4 Case 3, Step 1: Maturing Technology

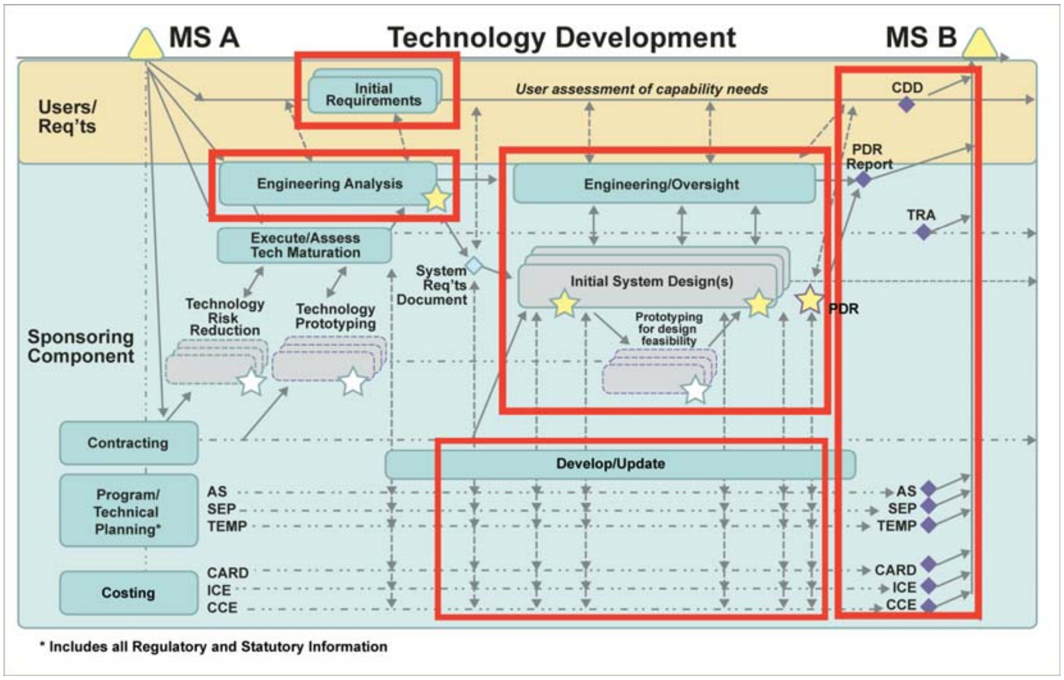

Figure 4-5 Case 3, Step 2: End Item Design

In Case 4 (Figure 4-6), several possible design solutions may exist, and the technology issues are different for each approach. To address this case, Figure 4-6 displays TD phase activities, which focus on multiple design competitors requiring prototypes to demonstrate technical feasibility of their designs, all before Milestone B. In this case, the TDS would establish this path including CTE prototyping, if required, as part of the preliminary design. The systems engineering team develops the SRD, updates the SEP, and provides input to the RFP for the competing preliminary design contracts. The technology development approach is based on competitive designs with supporting technology prototypes to demonstrate technology feasibility.

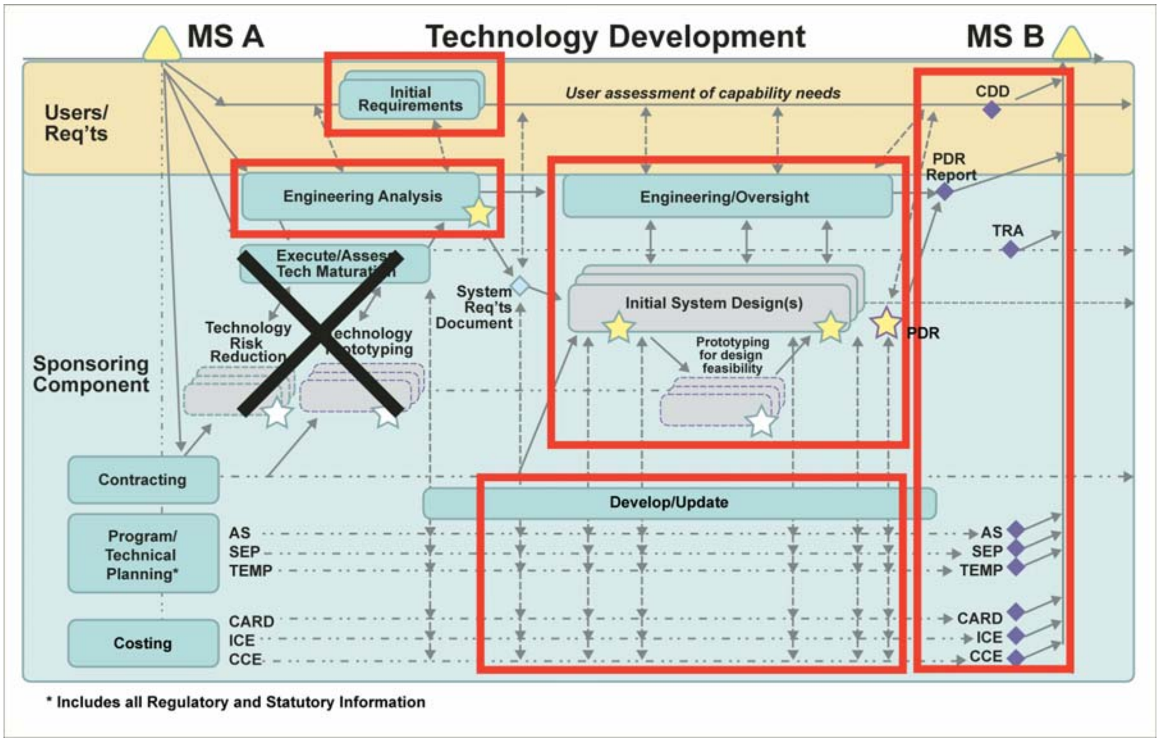

Figure 4-6 Case 4: Several Designs with Differing Issues

These four cases are only illustrations of how MSA analysis, both as part of the AoA and part of the engineering analysis of the recommended system solutions, forms the basis of a plan for technology development suited to the specific needs of a particular program. They demonstrate the types of pre-Milestone A engineering analyses the program office will need in order to make a program decision based on a solid technical foundation.

5 Conclusion

Changes in DoDI 5000.02 place added emphasis on the early phases of acquisition to ensure that there is sufficient understanding of the available solution options and risks to make an informed acquisition program decision at Milestone B. Systems engineering plays a key role in these early phases by providing the technical formation for program decisions. The pre-Milestone A engineering analysis is particularly critical because it informs the decision made during the now-critical TD phase of the acquisition process. The TD phase prototyping and preliminary design results provide the technical basis for determining achievable cost, schedule, and performance for a prospective program.

Acronyms

AoA	Analysis of Alternatives
APB	Acquisition Program Baseline
AS	Acquisition Strategy
CARD	Cost Analysis Requirement Description
CCE	Component Cost Estimate
CDD	Capabilities Development Document
CM	configuration management
CONOPS	Concept of Operations
CPI	critical program information
CTE	critical technology element
EMD	Engineering and Manufacturing Development (phase)
FFRDC	Federally Funded Research and Development Center
ICD	Initial Capabilities Document
ICE	Independent Cost Estimate
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
IPT	Integrated Product Team
IT	information technology
MDA	Milestone Decision Authority
MDD	Materiel Development Decision
MS	Milestone
MSA	Materiel Solution Analysis (phase)
PDR	Preliminary Design Review
POM	Program Objectives Memorandum
RFP	request for proposal
S&T	science and technology
SEMP	Systems Engineering Master Plan
SEP	Systems Engineering Plan
SFR	System Functional Requirements
SoS	system of systems
SRD	System Requirements Document
SRR	System Requirements Review
TD	Technology Development (phase)
TDS	Technology Development Strategy
TEMP	Test and Evaluation Master Plan
TES	Test and Evaluation Strategy
TRA	Technology Readiness Assessment

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