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Identifying and Assessing Life-Cycle-Related Critical Technology Elements (CTEs) for Technology Readiness Assessments (TRAs)

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Preface

The Institute for Defense Analyses (IDA) prepared this paper for the Office of the Deputy Under Secretary of Defense for Science and Technology (ODUSD(S&T)) under the "Technology Readiness Assessments and Analyses" task. The material in this paper was presented at the National Defense Industrial Association's 9th Annual Systems Engineering Conference in October 2006 and will be presented at the 23rd Annual National Test and Evaluation Conference in March 2007.

This paper partially fulfills the task objective of developing material on the performance and review of technology assessments and associated processes. The author would like to thank Lance Hancock and Lance Roark of IDA for their technical reviews of this paper.

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Executive Summary

Thus far, Technology Readiness Assessment (TRA) guidance has primarily focused on (1) hardware and software critical technology elements CTEs that affect performance and (2) manufacturing-related CTEs. While life-cycle-related technologies can be addressed in the current TRA process, in general, they receive little emphasis. This paper describes how to increase attention on such technologies.

A TRA is a regulatory information requirement for all acquisition programs. It is a systematic, metrics-based process that uses Technology Readiness Levels (TRLs) to assess the maturity of CTEs. The assessment is made by a panel of subject matter experts (SMEs) independent of the program. The Program Manager (PM), Program Executive Officer (PEO), and Component Acquisition Executive (CAE) use the TRA results to optimize the acquisition strategy, determine the capabilities to be deferred to the next increment, and enhance technology investment. The PM also uses the expertise of the assessment team and the rigor and discipline of the process for an early in-depth review of the conceptual product baseline and periodic in-depth reviews of maturation events. The TRA also highlights (and, in some cases, discovers) critical technologies and other potential technology risk areas that require the PM's attention (and possibly additional resources). In addition, the Milestone Decision Authority (MDA)—the single focal point for programmatic decisions—uses the information from a TRA to support a decision to initiate a program at Milestone B and then later to support a decision to enter Low-Rate Initial Production (LRIP) at Milestone C.

While any CTE has an effect throughout the life of a system, this paper uses the term "life-cycle-related technologies" to mean those technologies that affect system supportability cost and/or time. They can reduce the logistics footprint, improve reliability/maintainability, lower operating support or maintenance manpower requirements, improve training, enhance human factors interactions, increase operational availability or readiness, or improve the ability to upgrade of the system.

To improve the focus on life-cycle-related technologies during CTE identification, experts in the life-cycle-related areas of the program should be part of the PM's technical support team that makes the initial CTE determination and of the independent review team, which can suggest changes. Also, when deciding whether a CTE candidate is critical, additional questions should be asked to ascertain whether a candidate life-cycle technology would have a "significant" affect on life-cycle affordability:

1. Is the affordability benefit *significant* over the life cycle, where significance is based on the judgment of the independent SME panel?

2. Is the affordability benefit enabled by a technological solution and not solely through engineering design?

These questions are intended to highlight whether the allocated baseline design configuration contains life-cycle-related CTEs and must be answered affirmatively.

While some technologies may be critical solely on a life-cycle affordability basis, others may be critical from multiple perspectives. Consequently, once a CTE has been identified from a performance perspective, it should also be determined whether it is a CTE from a life-cycle point of view. TRAs evaluate the extent to which a program is ready to transition to the next phase of development—an evaluation that is based on the maturity of the critical technologies. Therefore, if a technology is critical from both perspectives (performance-related maturity and life-cycle-related maturity), it should be ***assessed from both perspectives***. Establishing performance-related maturity is not a sufficient condition for assuming life-cycle-related maturity. Separate TRLs should be assigned.

CTE maturation should be monitored throughout the System Development and Demonstration (SDD) Phase of the acquisition framework. All CTEs should have a maturation plan that shows a roadmap for reaching TRL 8 (actual system proven through successful mission operations). An independent technical authority should monitor the status of CTE maturation plans during systems engineering technical reviews. In addition, these technical reviews will be the forum for identifying any new life-cycle-related CTEs that emerge as part of the solution to a problem encountered during system development.

Identifying and Assessing Life-Cycle-Related
Critical Technology Elements (CTEs)
for Technology Readiness Assessments (TRAs)

A. Background

A Technology Readiness Assessment (TRA) is a regulatory information requirement for all acquisition programs. It is a systematic, metrics-based process that uses Technology Readiness Levels (TRLs) to assess the maturity of critical technology elements (CTEs). The assessment is made by a panel of subject matter experts (SMEs) independent of the program. A summary description of CTEs and TRLs from the *TRA Deskbook*[1] is as follows:

- 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 and with acceptable production and operation costs and if the technology element or its application is either new or novel.

- TRLs indicate what has been accomplished in the development of a technology from several perspectives: theory to laboratory to field, relevant environment to operational environment, subscale to full scale, breadboard to brassboard to prototype, and partial performance to full performance. TRLs *do not* indicate that the technology is right for the job or that the application of the technology will result in successful development of the system, and TRLs do not address risk or system integration.[2]

Many programs that begin development with immature technologies have experienced significant technical difficulties, which lead to schedule delays and cost overruns. The TRA was established as a control mechanism to identify and monitor the maturity of critical technologies, based on what has been accomplished. The Milestone Decision Authority (MDA)—the single focal point for programmatic decisions—uses the information from a TRA to support a decision to initiate a program at Milestone B and then later to support a decision to enter Low-Rate Initial Production (LRIP) at Milestone C. Congress has recognized the relationship between program success and TRAs. At program initiation, the MDA must certify to Congress that the technology

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[1] *Department of Defense Technology Readiness Assessment (TRA) Deskbook,* prepared by the Deputy Under Secretary of Defense for Science and Technology (DUSD(S&T)), May 2005, http://www.defenselink.mil/ddre/weapons.htm.

[2] The *TRA Deskbook* addresses hardware-, software-, and manufacturing-related technologies. The TRL definitions for the hardware- and manufacturing-related technologies are identical but are different from the TRL definitions for the software-related technologies. This paper addresses only hardware- and software-related technologies.

in Major Defense Acquisition Programs (MDAPs) has been demonstrated in a relevant environment.[3] Waivers of this certification for national security must be justified.[4]

The Program Manager (PM), Program Executive Officer (PEO), and Component Acquisition Executive (CAE) use the TRA results to optimize the acquisition strategy, determine the capabilities to be deferred to the next increment, and enhance technology investment. In addition, the PM uses the expertise of the independent assessment team (i.e., the SMEs) and the rigor and discipline of the process for an early in-depth review of the conceptual product baseline and periodic in-depth reviews of maturation events. The TRA also highlights (and, in some cases, discovers) critical technologies and other potential technology risk areas that require the PM's attention (and possibly additional resources).

Thus far, TRA guidance has focused primarily on (1) hardware and software CTEs that affect performance and (2) manufacturing-related CTEs. While life-cycle-related technologies can be addressed in the current TRA process, in general, they receive little emphasis. This paper describes how to increase attention on such technologies.

B.   Significance of Life-Cycle-Related Technologies to TRAs

While any CTE has an effect throughout the life of a system, this paper uses the term "life-cycle-related technologies" to mean those technologies that affect system supportability cost and/or time. They can reduce the logistics footprint, improve reliability/maintainability, lower operating support or maintenance manpower requirements, improve training, enhance human factors interactions, increase operational availability or readiness, or improve the ability to upgrade of the system.

Examples of life-cycle-related technologies include

- Corrosion-resistant materials

- Thermal protection materials

- Supportable low-observable (LO) materials

- Obsolescence mitigation technologies

- Technical data automation technologies

- Material handling technologies

- Simulators or training simulations

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[3]   Section 2366a of Title 10, United States Code (U.S.C.), as enacted by Section 801 of the National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2006 (P.L. 109-163). [**Editor's note:** *The Public Law (P.L.) number follows the form **P.L. 109-163**, meaning this law is the 163rd law passed by the 109th Congress.*]

[4]   The MDA can waive any certification requirement of P.L. 109-163 (as enacted by Section 801) if the Department is unable to meet national security objectives. The MDA has to submit the waiver, the determination, and reasons for the determination, in writing, to the congressional defense committees within 30 days of authorizing the waiver.

- Autonomic[5] logistics sensors, data links, or messaging transmission

- Advanced technologies that affect human factors such as safety and occupational health, habitability, or cognitive or physical requirements

- Analysis technologies, such as automated diagnostics and prognostics

- Methods/algorithms for sensing or trend analysis

- Technologies that enable open systems architectures.

The TRA process should be concerned with such technologies for many reasons. First, from a definitional perspective, the CTE definition encompasses all elements of the life cycle in terms of development, production, and operating and support (O&S) costs.

Second, from a policy perspective, life-cycle-related issues affect military capability, and, therefore, greater emphasis is being placed on the technologies that enable this capability. Department of Defense Instruction (DoDI) 5000.2[6] states that "The project shall exit Technology Development when an *affordable increment* of militarily-useful capability has been identified, the technology for that increment has been demonstrated in a relevant environment, and a system can be developed for production within a short timeframe (normally less than 5 years); or when the MDA decides to terminate the effort." Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 3170.01E[7] defines *increment* as "a militarily useful and *supportable* operational capability that can be effectively developed, produced or acquired, deployed, and sustained. Each increment of capability will have its own set of threshold and objective values set by the user. Spiral development is an instance of an incremental development strategy where the end state is not known. Technology is spiraled to maturity and injected into the delivery of an increment of capability." Accordingly, mobility and logistics footprint are military capabilities and reliability and maintainability are military performance parameters.

Finally, from a real-life experience perspective, O&S costs will continue to increase, thereby making life-cycle-related technologies even more critical. The percentage of systems passing operational tests from a suitability[8] perspective[9] has experienced a recent drop (see

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[5] Autonomic refers the ability respond to problems, repair faults, and recover from system outages without the need for human intervention.

[6] DoDI 5000.2, *Operation of the Defense Acquisition System*, May 12, 2003.

[7] CJCSI 3170.01E, *Joint Capabilities Integration and Development System*, May 11, 2005.

[8] According to CJCSI 3170.01E, operational suitability is the degree to which a system can be placed and sustained satisfactorily in field use, with consideration given to availability; compatibility; transportability; interoperability; reliability; wartime usage rates; maintainability; environmental, safety, and occupational health risks; human factors; habitability; manpower; logistics supportability; natural environment effects and impacts; and documentation and training requirements.

[9] The trend has been that more systems are passing operational tests from an effectiveness perspective. This trend is primarily the result of a change in testing philosophy. Previously, most tests were conducted on a pass-fail basis against a specific (and sometimes arbitrary) required performance value or level. In today's environment, testing is based on the ability to accomplish the mission.

Figure 1). Interviews with several SMEs attribute this drop to an overemphasis on performance by program management.
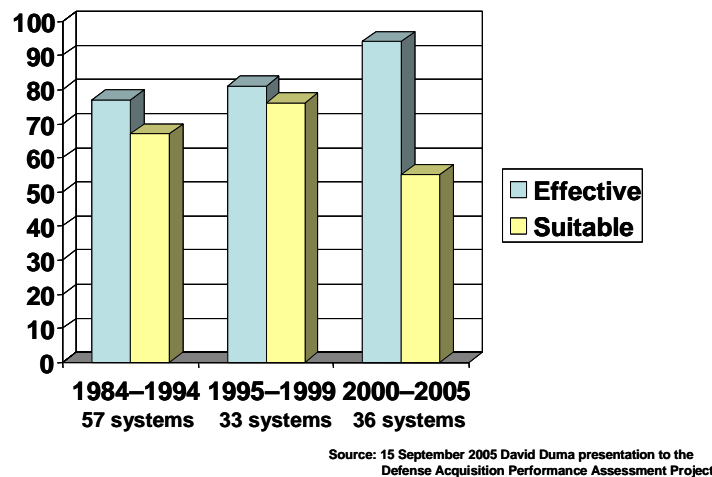
Figure 1. Percentage of Systems Passing an Operational Test

Resources for suitability are often diverted to deal with technical performance problems, and this means that technical suitability issues have to be solved after production when such solutions will prove more costly and cause delays to a program. Recently, an abundance of software development problems have exacerbated these diversions.

C. Life-Cycle CTE Identification

The *TRA Deskbook* describes a three step process used to identify CTEs:

- **Step 1.** Use the work breakdown structure (WBS) or system architecture for information technology systems to identify CTE candidates by

  – Establishing the functions to be performed by each system, subsystem, or component throughout the WBS, determining how these functions will be accomplished, and identifying the technologies needed to perform these functions at the desired level.

- **Step 2.** Determine whether the candidate technology is critical to the program by answering one of the following questions affirmatively:

  – Does the technology directly affect an operational requirement?

  – Does the technology significantly effect an improved delivery schedule?

  – Does the technology significantly affect the affordability of the system?

- **Step 3.** Determine whether the candidate technology is new or novel by answering one of the following questions affirmatively:

  – Is the technology new or novel?

  – Has the technology been modified?

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> – Has the technology been repackaged such that a new, relevant environment is realized?
>
> – Is the technology expected to operate in an environment and/or achieve a level of performance beyond its original design intention or demonstrated capability?

These steps are normally conducted by the PM (and his/her technical support staff). As a best practice, the independent panel of SMEs who make the readiness assessments for the technology should also be asked to verify the PM's initial CTE list and determine whether additions or deletions are warranted. Expanding the third question in step 2 could increase the likelihood of identifying life-cycle-related technologies. Step 2 would become:

- **Step 2 revised.** Determine whether the candidate technology is critical to the program by answering one of the following questions affirmatively:

  - Does the technology directly effect an operational requirement?

  - Does the technology have a significant effect on an improved delivery schedule?

  - Does the technology have a significant effect on the ***life-cycle*** affordability of the system?

This revised question can be answered affirmatively from an acquisition cost perspective with a "yes" answer to the following amplifying questions:

- Will the acquisition cost of the component or subsystem that uses this technology be significantly higher without the technology?

The revised question can also be answered affirmatively from an O&S cost structure perspective with a "yes" answer to any of the following amplifying questions:

- Does the technology significantly reduce the logistics footprint?

- Does the technology significantly improve reliability or maintainability?

- Does the technology significantly lower operational, support, or maintenance manpower requirements?

- Does the technology significantly improve training by some combination of lowering the resources needed for training or boosting the effectiveness of the training?

- Does the technology significantly increase operational availability or readiness?

- Does the technology significantly improve the ability to upgrade the system?

These amplifying questions are not intended to suggest that technologies not encompassed in the CTE definition should be assessed in a TRA. They are, however, intended to highlight whether the allocated baseline design configuration contains life-cycle-related CTEs. Two conditions must be met to answer affirmatively:

1. The affordability benefit must be *significant* over the life cycle, where significance is based on the judgment of the independent SME panel.

2. The affordability benefit must be enabled by a technological solution and not solely through engineering design.

In some cases, a performance-related CTE can also be designated as a life-cycle-related CTE (see Figure 2). The technology would have to be "new or novel" and would have to affect an operational requirement and significantly affect the life-cycle affordability of the system. The TRA's purpose is to determine whether critical technologies are mature enough for the program to enter the next phase of development. Since maturity from a performance perspective does not necessarily imply maturity from a life-cycle-related perspective, technologies identified as critical from two perspectives should, therefore, be *assessed from both perspectives* in the TRA.

- *Does the technology directly affect an operational requirement?* Yes. The performance and capabilities of current airborne radars are limited by the speed of the mechanically scanned antennas. The APG-79's beam can be steered close to the speed of light, thereby enabling superior performance, including air-to-air tracking at very long detection ranges—almost simultaneous air-to-air and air-to-surface mode capability—and improved situational awareness.

- *Does the technology have a significant affect on the life-cycle affordability of the system?* Yes. The technology enables a modular design, open systems architecture that leads to rapid repairs and the ability to be upgrded easily. Because the array is solid state, mechanical breakdowns are virtually eliminated. Its predicted mean time between critical failures (MTBCFs) is greater than 15,000 hours. The MTBCF for the entire system will be greater than 1,250 hours.

- *Is the technology new or novel?* Yes. Everything in the system is new—from front-end array to back-end processor and operational software.

Consequently, the active electronically scanned array (AESA) radar is a CTE from performance and life-cycle affordability viewpoints.

Figure 2. Illustrative Example of a CTE That Is Both Performance Related and Life Cycle Related: the AN/APG-79 AESA Radar, a Key Element in the F/A-18 E/F Super Hornet Block II Upgrades[10]

D. Assessing the Maturity of Life-Cycle-Related CTEs

The TRL tables in the *TRA Deskbook* were designed to assess the maturity of hardware-, software-, and manufacturing-related technologies. The columns in these tables provide

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[10] Sources: All source material copyright Raytheon Company – Rights reserved under copyright laws of the United States. Permission is granted by Raytheon Company for the U.S. Government to copy this material for evaluation purposes only.

(1) June 28, 2005, Raytheon News Release, *Raytheon's Revolutionary APG-79 AESA Radar is Awarded a $580 Million Multi-Year Procurement Contract by the Boeing Company,* http://www.prnewswire.com/cgi-bin/micro_stories.pl?ACCT=149999&TICK=RTN&STORY=/www/story/06-28-2005/0003985043&EDATE=Jun+28,+2005.

(2) November 20, 2002, Raytheon News Release, *Raytheon Demonstrates First Next-Generation AESA Capability at APG-79 Event,* http://www.raytheon.com/newsroom/briefs/112002.htm.

(3) Raytheon AN/APG-79 AESA Data Sheet, http://www.raytheon.com/products/stellent/groups/sas/documents/legacy_site/cms01_050831.pdf.

definitions, descriptions, and supporting information for the applicable TRLs. The "supporting information column" is a brief explanation of some specific criteria to apply (sufficient conditions) when assigning a TRL to a technology.

All the information in these tables applies to life-cycle-related CTEs. An assessment should use either the software or the hardware definitions and descriptions verbatim, depending on the nature of the technology. However, assessing the maturity of life-cycle-related CTEs can be aided by supplementing the "supporting information column" with some clarifying examples tailored to such technologies. The primary reason is this: Beyond TRL 3 (analytical and experimental critical function and/or characteristic proof of concept), the long-term effects of life-cycle-related technologies must be demonstrated in a short period of time.

Under circumstances in which the long-term effects of the life-cycle-related CTE can be calculated analytically and the risk of error is minimal,[11] the existing supporting information (for TRL 4 and above) is sufficient (e.g., technologies that reduce manpower O&S requirements through automation, enhance training, or improve the ability of the system to be upgraded) (see Figures 3 and 4).

When long-term effects cannot be accurately calculated analytically and the risk of a miscalculation is large (e.g., accelerated life testing of explosives), the usual supporting information for TRL 4 and above should be augmented or tailored for the specific situation. For example,

- For technologies that improve reliability/maintainability and correspondingly reduce the logistics footprint and operating, support, or maintenance manpower requirements,[12] the additional supporting information should focus on the performance of the end item in these areas (see Figure 5).

- For technologies used to protect against the environment,[13] the additional supporting information should focus on the performance of the material being tested (see Figure 6).

- For on-board and off-board technologies for analysis, status, or diagnosis of failure, the additional supporting information should focus on accuracy (see Figure 7).

Tables 1–6 suggest additional supporting information for the hardware TRL data for technologies used to improve reliability/maintainability and to protect against the environment. These tables also suggest additional supporting information for the software TRL data for analysis technologies. In these situations, the technologies are often based on commercial-off-the-shelf (COTS) products or on similar applications in other Department of Defense (DoD) systems. Therefore, the necessary supporting information, as described in the tables, might be obtained from such sources.

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[11] Risk is associated with the calculations themselves and with the effects of errors in the calculations.

[12] Includes redesigns either for reliability improvements or because of obsolescence mitigation. Often, a form-fit-function replacement for an existing item but may also include increased functionality.

[13] Such technologies also often protect the environment.

Description: The CVN-21 program is designing the aircraft carrier for the 21st Century, as the replacement for the *Nimitz* Class nuclear aircraft carriers. Improved weapons handling is one of the new features of this ship class. The proposed shipboard weapons loader (SWL) combines human amplification technology with a self-powered platform, high-torque electric actuator/motors, and variable geometry ilonator wheels. This will provide a capability for a single operator to upload and download munitions while reducing operator workload and life-cycle cost. The SWL could, therefore, be classified as a life-cycle-related CTE.[14]

Example of an Assessment: TRL 4 (component and/or breadboard validation in a laboratory environment) was achieved in successful demonstrations of the SWL in shore-based industrial environments with a single human operator. Ship manpower reductions were confirmed across the entire fleet through a comparison with current SWL crew requirements. Planned demonstration of shipboard prototypes with human system controls and ship's motion compensation under relevant shipboard environments would be required to achieve TRL 6.

Figure 3. Illustrative Example of a Life-Cycle-Related CTE Where Existing TRL Supporting Information Is Sufficient for Assessing Maturity: the SWL for the CVN-21

Description: As the world's only fifth-generation fighter, the F-22 Raptor is being developed to counter increasingly sophisticated air and ground threats that the F-15 cannot readily defeat. The F-22's requirements emphasize the reliability and maintainability of systems. By replacing paper-based technical orders (TOs), the new Integrated Management Information System (IMIS) increases the accuracy of technical data, accelerates the preparation of work orders and parts' requisitions, and improves the performance of maintenance specialists and technicians. IMIS could, therefore, be classified as a life-cycle-related CTE.[15]

Example of an Assessment: TRL 6 (system/subsystem model or prototype demonstration in a relevant environment) was accomplished in a field test of a prototype system that was near the desired configuration. The tests were performed on three F-16 subsystems. Test results demonstrated across-the-board performance improvements, as measured by reduced error rates and fewer maintenance man-hours.[16] These results can be extrapolated to the entire F-22 fleet with little risk of error.

Figure 4. Illustrative Example of a Life-Cycle Related CTE Where Existing TRL Supporting Information Is Sufficient for Assessing Maturity: the IMIS for the F-22

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14 The SWL is a CTE for the CVN-21. It was rated TRL 4 in the TRA.

15 No TRA has been done for the F-22.

16 For more information, see IDA Paper P-3173, *Costs and Benefits of the Integrated Maintenance Information System (IMIS)*, May 1996.

Description: The C-5 Galaxy is a heavy cargo transport plane designed to provide strategic airlift for the deployment and supply of forces. The C-5 Reliability Enhancement and Re-Engining Program (RERP) is a comprehensive effort to improve reliability, maintainability, and availability. While this program encompasses the upgrade of more than 50 items, the greatest expected benefit will be achieved by replacing the current engine with a new engine (along with new pylons, wing attachment fittings, software, and thrust reversers). Therefore, the new propulsion system can be the source of several life-cycle-related CTEs.

Example of an Assessment:[17] TRL 7 (system prototype demonstration in an operational environment) was accomplished because of commercial experience with the General Electric CF-680C2 engine being used to replace the current TF39 engine. The increase of engine hardware reliability to more than 10,000 hours of engine time on wing has been demonstrated from commercial experience. Commercial data have also established "fix rates" as follows: at least 30.1 percent of failures will be corrected within 4 hours, at least 62.9 percent of failures will be corrected within 12 hours, and at least 82.4 percent of failures will be corrected within 24 hours. These fix rates will enable a significant increase in sortie generation. One difference from the commercial version is that new pylons, wing attachment fittings, software, and thrust reversers will be used on the C-5. The new pylons and wing attachment fittings have been employed successfully in similar applications and operational environments. Most of the basic algorithms in the engine software will not change. While the new engine thrust reverser is COTS, the C-5 is required to use its thrust reverser in-flight for rapid descent capability—a maneuver that is not made in commercial applications.

Figure 5. Illustrative Example of Assessing the Maturity of Life-Cycle-Related CTEs To Improve Reliability/Maintainability: the C-5 RERP

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[17] The C-5 TRA identified the components discussed herein as CTEs. The TRL assessment in the actual TRA differed from this example.

Description: The new Landing Helicopter Assault Replacement (LHA-R) amphibious assault ship is slated to replace LHA-1 Class ships. Because the LHA-R will be an enhanced aviation variant of the LHD-8, redesign plans were developed for the affected systems. There is, however, an opportunity to reduce life-cycle costs significantly by using advanced high solid, low-edge retentive tank coatings instead of solvent-based paints. In the last decade, the represervation of tanks has represented the highest annual maintenance cost to the fleet. These new advances could be classified as a life-cycle-related CTE.[18]

Example of an Assessment: An abundance of commercial data is available on high solid, low-edge retentive coatings. These new coatings have an estimated service life of 20 years as compared with the 2- to 7-year service life of the current coatings. Savings are realized from reduced inspection, cleaning, preparation, and painting requirements. In addition, applying the new coatings is less labor intensive because fewer coats are needed. Overall, a TRL 7 (system prototype demonstration in an operational environment) can be assigned to this CTE.

Figure 6. Illustrative Example of Assessing the Maturity of Life-Cycle-Related Environmental Protection CTEs: High Solid, Low-Edge Retentive Tank Coatings for the LHA-R Amphibious Assault Ship

Description: The extensive use of predictive maintenance, conducted by networked on-board diagnostics and prognostics that pulse the system when issues arise (or are expected), is an important component of the Joint Integrating Concept for Joint Logistics. Such anticipatory knowledge provides commanders important advantages for successfully achieving the mission. The Future Combat Systems (FCS), therefore, plans to use embedded predictive logistics sensors and algorithms and could classify them as life-cycle-related CTEs.[19]
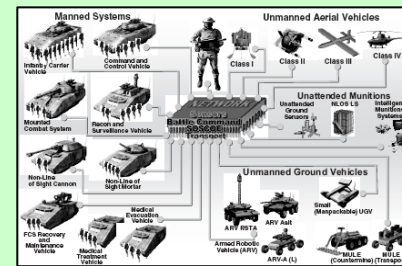
Example Assessment: When failures are random, physics-of-failure models do not exist. Consequently, a statistical approach to prediction must be taken; however, currently, no data are available to support such an approach for the FCS. In the electronics area, some work is underway to model degradations as a result of vibrations and thermal cycles. This work, however, is relatively immature—only TRL 4 [module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment)] is applicable. The Army is also deploying a health monitoring system for the Patriot Advanced Capability (PAC) missile system. Thus, while some FCS mission-critical systems may be TRL 5 (module and/or subsystem validation in a relevant environment), most are TRL 4, and, overall, an embedded predictive logistics sensors and algorithms CTE would be TRL 4.

Figure 7. Illustrative Example of Assessing the Maturity of Life-Cycle-Related Analysis CTEs: Embedded Predictive Logistics Sensors and Algorithms for the Army's FCS

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[18] The LHA-R TRA identified no CTEs. However, the Defense Acquisition Board (DAB) was made aware of an issue concerning edge retentive tank coating opportunities. A business-case analysis was requested.

Table 1. Additional Life-Cycle-Related Supporting Information for TRL 4

Hardware TRL 4 Definition	Hardware TRL 4 Description	Hardware TRL 4 Supporting Information
Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
Additional hardware supporting information for technologies to improve reliability/maintainability		
Analytical efforts at the part or component level that estimate reliability (or reliability improvement if comparing with something that already exists). These efforts may encompass both a failure mode and effects analysis (FMEA) and failure rate calculations for each of the failure mechanisms. Alternative corrective and/or preventive actions that could mitigate the most significant failure mechanisms should be identified.		
Additional hardware supporting information for technologies used to protect against the environment		
Analyses of how the environmental protection material (e.g., coatings, films, composites, and so forth) will be formed or integrated chemically, mechanically (e.g., materials and fibers), and/or through special processes (e.g., heat treatment). Basic properties characterized potentially through virtual modeling. High-fidelity simulations conducted to predict behavior in the field. Predicted behavior meets expectations/requirements.		
Software TRL 4 Definition	Software TRL 4 Description	Software TRL 4 Supporting Information
Module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment).	Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy elements as appropriate. Prototypes developed to demonstrate different aspects of the eventual system.	Advanced technology development, stand-alone prototype solving a synthetic full-scale problem, or standalone prototype processing fully representative data sets.
Additional software supporting information for analysis technologies		
An initial determination of the analysis input data (e.g., sensor type and placement and historical maintenance/failure rates) has been made. First-cut rules established. These rules that define the maintenance actions to be taken as a function of various combinations of the input data.		

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[19] At one time, the FCS TRA identified embedded predictive logistics sensors and algorithms as a CTE. The TRL assessment in the actual TRA differed from this example.

Table 2. Additional Life-Cycle-Related Supporting Information for TRL 5

Hardware TRL 5 Definition	Hardware TRL 5 Description	Hardware TRL 5 Supporting Information
Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
Additional hardware supporting information for technologies to improve reliability/maintainability		
Where warranted by risk, accelerated life-cycle testing, or its equivalent, is conducted at the part or component level in high-stress environments. Results from analysis of test results, generally measured by the mean time between failure (MTBF), provide estimates of product's life and performance under normal conditions. Reliability growth modeling indicates future levels of reliability and the time when such levels will be achieved. Estimates meet life-cycle expectations/requirements.		
Additional hardware supporting information for technologies used to protect against the environment		
For material formed in a laboratory environment, basic properties have been verified by testing. Variations from properties characterized (perhaps virtually) at TRL 4 are acceptable. Ability to use the material for the intended application in terms of form, fit, and function has been verified.		
Software TRL 5 Definition	Software TRL 5 Description	Software TRL 5 Supporting Information
Module and/or subsystem validation in a relevant environment.	Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment.	System architecture diagram around technology element with critical performance requirements defined. Processor selection analysis, Simulation/Stimulation (Sim/Stim) Laboratory buildup plan. Software placed under configuration management. COTS/GOTS (government-off-the-shelf) elements in the system software architecture are identified.
Additional software supporting information for analysis technologies		
Test data are developed for verifying that the rules established at TRL 4 are working as intended. Test results indicate adequate performance. Process defined for integrating the output of on-board analysis technologies with other off-board information.		

Table 3. Additional Life-Cycle-Related Supporting Information for TRL 6

Hardware TRL 6 Definition	Hardware TRL 6 Description	Hardware TRL 6 Supporting Information
System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
Additional hardware supporting information for technologies to improve reliability/maintainability		
Analytical efforts at the subsystem level that estimate reliability (or reliability improvement if comparing to something that already exists). Efforts may encompass both an FMEA and failure-rate calculations for each of the subsystem failure mechanisms. Alternative corrective and/or preventive actions that could mitigate the most significant failure mechanisms should be identified. Maintainability analyses conducted to determine reliability-centered (failure-based) maintenance and condition-based maintenance strategies as well as a level of repair determination. Estimated support man-hours and spare parts' needs meet expectations/requirements. Form-fit-function performance ensured.		
Additional hardware supporting information for technologies used to protect against the environment		
Material is tested in a laboratory environment to provide assurance of its performance throughout its intended life cycle. Deliberately stressful/relevant environments are used to determine whether any degradation in performance occurs against known standards. Material interaction testing is conducted to ensure that no adverse chemical or other reactions occur in either the components being protected or other adjacent parts of the system.		
Software TRL 6 Definition	**Software TRL 6 Description**	**Software TRL 6 Supporting Information**
Module and/or subsystem validation in a relevant end-to-end environment.	Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.	Results from laboratory testing of a prototype package that is near the desired configuration in terms of performance, including physical, logical, data, and security interfaces. Comparisons between tested environment and operational environment analytically understood. Analysis and test measurements quantifying contribution to system-wide requirements such as throughput, scalability, and reliability. Analysis of human-computer (user environment) begun.
Additional software supporting information for analysis technologies		
Verify that faults can be detected/predicted using known faults in a simulated real environment, such as a test cell or test platform not in use. Both Type I errors (actual faults not detected) and Type II errors (false positives) are within acceptable limits.		

Table 4. Additional Life-Cycle-Related Supporting Information for TRL 7

Hardware TRL 7 Definition	Hardware TRL 7 Description	Hardware TRL 7 Supporting Information
System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). Examples include testing the prototype in a test bed aircraft.	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
Additional hardware supporting information for technologies to improve reliability/maintainability		
Where warranted by risk, accelerated life-cycle testing, or its equivalent, is conducted at the subsystem-level prototype in high-stress operational environments. Results from the analysis of test results, generally measured by MTBF, provide estimates of a product's life and performance under normal conditions. Reliability growth modeling indicates future levels of reliability and the time when such levels will be achieved. Estimates meet life-cycle expectations/requirements. Refinement of maintainability analyses results based on accelerated life-cycle testing. Estimated support man-hours and spare parts' needs continue to meet expectations/requirements.		
Additional hardware supporting information for technologies used to protect against the environment		
Operational exposure testing conducted on multiple subsystems for extended periods of time (concern is with calendar time, not operating time). Inspections performed throughout the testing period. Performance measured, in part, by man-hours expended or scrap rate. Performance is verified to meet expectations/requirements.		
Software TRL 7 Definition	Software TRL 7 Description	Software TRL 7 Supporting Information
System prototype demonstration in an operational high-fidelity environment.	Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.	Critical technological properties are measured against requirements in a simulated operational environment.
Additional software supporting information for analysis technologies		
Verify that faults can be detected/predicted using known faults in a real environment, such as a test platform not in use. Both Type I errors (actual faults not detected) and Type II errors (false positives) are within acceptable limits. Process for integrating the output of on-board analysis technologies with other off-board information is verified.		

Table 5. Additional Life-Cycle-Related Supporting Information for TRL 8

Hardware TRL 8 Definition	Hardware TRL 8 Description	Hardware TRL 8 Supporting Information
Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
Additional hardware supporting information for technologies to improve reliability/maintainability		
Continuation of tests conducted to measure whether the technology has achieved TRL 7, failure rates, MTBF growth charts, maintenance hours per operational hour. Operational Test and Evaluation (OT&E) suitability reports.		
Additional hardware supporting information for technologies used to protect against the environment		
Continuation of tests conducted to measure whether the technology has achieved TRL 7. OT&E suitability reports.		
Software TRL 8 Definition	Software TRL 8 Description	Software TRL 8 Supporting Information
Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
Additional software supporting information for analysis technologies		
Verify that faults can be detected/predicted within acceptable limits using production-representative platforms. OT&E suitability reports.		

Table 6. Additional Life-Cycle-Related Supporting Information for TRL 9

Hardware TRL 9 Definition	Hardware TRL 9 Description	Hardware TRL 9 Supporting Information
Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in OT&E. Examples include using the system under operational mission conditions.	OT&E reports.
Additional hardware supporting information for technologies to improve reliability/maintainability		
O&S cost/failure data from the field.		
Additional hardware supporting information for technologies used to protect against the environment		
O&S cost/failure data from the field.		
Software TRL 9 Definition	**Software TRL 9 Description**	**Software TRL 9 Supporting Information**
Actual system proven through successful mission-proven operational capabilities.	Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system.	Production configuration management reports. Technology integrated into a reuse "wizard"; out-year funding established for support activity.
Additional software supporting information for analysis technologies		
Acceptability of Type I (actual faults not detected) and Type II (false positives) errors detected in the field.		

E.   Summary and Conclusion

Life-cycle-related technologies affect system supportability cost and/or time. They can reduce the logistics footprint; improve reliability/maintainability; lower operating, support, or maintenance manpower requirements; enhance training; enhance human factors interactions; increase operational availability or readiness; or improve the ability to upgrade the system.

While life-cycle-related technologies can be considered CTE candidates in the current TRA process, in general, they receive little emphasis. Increased attention on such technologies is supported by the CTE definition, the policy established in DoDI 5000.2 and CJCSI 3170.01E, and anticipated increases in O&S costs.

To improve the focus on life-cycle-related technologies during CTE identification, experts in the life-cycle-related areas of the program should be part of the PM's technical support team that makes the initial CTE determination and of the independent review team (i.e., the SMEs), which can suggest changes. Also, when deciding whether a CTE candidate is critical, additional questions should be asked to ascertain whether a candidate life-cycle technology would have a "significant" affect on life-cycle affordability:

1. Is the affordability benefit *significant* over the life cycle, where significance is based on the judgment of the independent SME panel?

2. Is the affordability benefit enabled by a technological solution and not solely through engineering design?

These questions are intended to highlight whether the allocated baseline design configuration contains life-cycle-related CTEs and must be answered affirmatively.

While some technologies may be critical solely on a life-cycle affordability basis, others may be critical from multiple perspectives. Consequently, once a CTE has been identified from a performance perspective, it should also be determined whether it is a CTE from a life-cycle point of view. TRAs evaluate the extent to which a program is ready to transition to the next phase of development—an evaluation that is based on the maturity of the critical technologies. Therefore, if a technology is critical from both perspectives (performance-related maturity and life-cycle-related maturity), it should be *assessed from both perspectives*. Establishing performance-related maturity is not a sufficient condition for assuming life-cycle-related maturity. Separate TRLs should be assigned.

The definitions, descriptions, and supporting information corresponding to the various TRLs, as described in the *TRA Deskbook*, apply to life-cycle-related technologies. However, under circumstances in which the long-term effects of a life-cycle-related CTE cannot be accurately calculated analytically and the risk of a miscalculation is large (e.g., accelerated life testing of explosives), the usual supporting information for TRL 4 and above should be augmented or tailored to the specific situation to help clarify the basis for a maturity assessment. This supplementary supporting information applies to (1) hardware TRL data for technologies to improve reliability/maintainability and technologies used to protect against the environment and (2) software TRL data for analysis technologies.

CTE maturation should be monitored throughout the System Development and Demonstration (SDD) Phase of the acquisition framework. All CTEs should have a maturation plan that shows a roadmap for reaching TRL 8 (actual system proven through successful mission operations). An independent technical authority should monitor the status of CTE maturation plans during systems engineering technical reviews. In addition, these technical reviews will be the forum for identifying any new life-cycle-related CTEs that emerge as part of the solution to a problem encountered during system development.

Glossary

ASEA	active electronically scanned array
CAE	Component Acquisition Executive
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
COTS	commercial-off-the-shelf
CTE	critical technology element
CVN	Carrier Vessel Nuclear
DAB	Defense Acquisition Board
DoD	Department of Defense
DoDI	Department of Defense Instruction
DUSD(S&T)	Deputy Under Secretary of Defense for Science and Technology
FCS	Future Combat Systems
FMEA	failure mode and effects analysis
FY	Fiscal Year
GOTS	government-off-the-shelf
IDA	Institute for Defense Analyses
IMIS	Integrated Management Information System
LHD	Amphibious Assault Ship
LHA-R	Landing Helicopter Assault Replacement
LO	low-observable
LRIP	Low-Rate Initial Production
MDA	Milestone Decision Authority
MDAP	Major Defense Acquisition Program
MTBCF	mean time between critical failures
MTBF	mean time between failure
NDAA	National Defense Authorization Act
O&S	operating and support
ODUSD(S&T)	Office of the Deputy Under Secretary of Defense for Science and Technology

OT&E	Operational Test and Evaluation
PAC	Patriot Advanced Capability
PEO	Program Executive Officer
PL	Public Law
PM	Program Manager
RERP	Reliability Enhancement and Re-Engining Program
SDD	System Development and Demonstration
Sim/Stim	Simulation/Stimulation
SME	subject matter expert
SWL	shipboard weapons loader
TO	technical order
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
U.S.C.	United States Code
WBS	work breakdown structure

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Life-cycle-related technologies affect system supportability cost and/or time. Such technologies affect military capability and are a key determinant of life-cycle costs. Because these technologies are not emphasized in the current Technology Readiness Assessment (TRA) process, this document is intended to improve the focus on life-cycle-related technologies in TRAs. It suggests questions that should be asked during critical technology identification to highlight whether the allocated baseline design configuration contains life-cycle-related critical technology elements (CTEs). It also provides additional supporting information that corresponds to the various Technology Readiness Levels (TRLs) that are used to assess the maturity of life-cycle-related technologies.

15. SUBJECT TERMS

affordability, critical technology element (CTE), life-cycle cost, Technology Readiness Assessment (TRA), Technology Readiness Level (TRL)

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