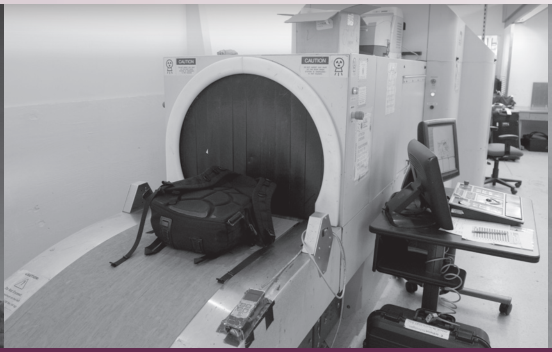
GAO BEST PRACTICES

Technology Readiness Assessment Guide

Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects



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From August 11, 2016 to August 10, 2017, GAO is seeking input and feedback on this Exposure Draft from all interested parties. See page 9 for more information.

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Best Practices Checklists

Abbreviations

AD2	Advancement Degree of Difficulty
COTS	commercial off the shelf
DDR&E	Deputy Director for Research and Engineering
DOD	U.S. Department of Defense

DOE	U.S. Department of Energy
DTRA	Defense Threat Reduction Agency
IRL	integration readiness level
ISRACO	International Systems Readiness Assessment Community of Interest
IT	information technology
MAIS	major automated information system
MDA	Milestone Decision Authority
MRL	Manufacturing Readiness Level
NASA	National Aeronautics and Space Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
R&D3	research and development degree of difficulty
RI3	risk identification, integration, and ilities
SEMP	systems engineering master plan
SRL	system readiness level
TBD	technical baseline description
TMP	technology maturation plan
TE	technology element
TPMM	technology program management model
TRA	technology readiness assessment
TRL	technology readiness level
USASMDC	U.S. Army Space and Missile Defense Command
WBS	work breakdown structure

Preface

The U.S. Government Accountability Office is responsible for, among other things, assisting the Congress in its oversight of the federal government, including agency acquisition programs and projects. Federal agencies spend billions of dollars each year to develop, acquire, and build major systems, facilities, and equipment, including fighter aircraft, nuclear waste treatment facilities, electronic baggage screening equipment, and telescopes for exploring the universe. Managing these complex acquisitions has been a long-standing challenge for federal agencies.

Many of the government's most costly and complex acquisition efforts require the development of cutting-edge technologies and their integration into large and complex systems. Such acquisition efforts may also use existing technologies, but in new applications or environments. At issue is not whether to take risks, but rather where and how to take them so they can be managed more effectively. For more than a decade, GAO has shown that using effective management practices and processes to assess how far a technology has matured and how it has been demonstrated are keys to evaluating its readiness to be integrated into a system and managed for risk in the federal government's major acquisitions.

A technology readiness assessment (TRA) is a systematic, evidence-based process that evaluates the maturity of hardware and software technologies critical to the performance of a larger system or the fulfillment of the key objectives of an acquisition program. TRAs, which measure the technical maturity of a technology or system at a specific point in time, do not eliminate technology risk, but when done well, can illuminate concerns and serve as the basis for realistic discussions on how to mitigate potential risks as programs move from the early stages of technology development, where resource requirements are relatively modest, to system development and beyond, where resource requirements are often substantial. In addition, TRAs help legislators, government officials, and the public hold government program managers accountable for achieving their technology performance goals.

This TRA guide (the Guide) is a companion to GAO's *Cost Estimating and Assessment Guide* and its *Schedule Assessment Guide*.[1] With this Guide, GAO

[1]GAO, *Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs,* GAO-09-3SP (Washington, D.C.: March 2009), and *Schedule Assessment Guide: Best Practices for Project Schedules*, GAO-16-89G (Washington, D.C.: December 2015).

intends to establish a methodology based on best practices that can be used across the federal government for evaluating technology maturity, particularly as it relates to determining a program or project's readiness to move past key decision points that typically coincide with major commitments of resources. Similar assessments can be made by technologists and program managers as knowledge-building exercises during the course of a project to help them evaluate technology maturity, gauge progress, and identify and manage risk. Existing TRA guidance in government agencies and industry may include similar strategies for evaluating technology maturity, but no widely held or accepted process exists for doing so. The science and technology, systems engineering, and program management communities each views technology readiness through its own lenses, which can make for variable and subjective TRA results. In addition, some agencies have deemphasized the use of TRAs or questioned their value. We hope that this Guide can help reinvigorate the use of TRAs in those organizations.

The Guide is intended to provide TRA practitioners, program and technology managers, and governance bodies throughout the federal government a framework for better understanding technology maturity, conducting credible technology readiness assessments, and developing plans for technology maturation efforts. Organizations that have developed their own guidance can use the Guide to support and supplement their practices. Organizations that have not yet developed their own policies can use it to begin establishing their own guidance. As a companion to GAO's cost and schedule assessment guides, this Guide can also help GAO and other oversight organizations evaluate agencies' basis for their conclusions and decisions about technology readiness.

We intend to keep the Guide current. We welcome comments and suggestions from experienced practitioners as well as recommendations from experts in the science and technology community, systems engineering, and program acquisition disciplines. Please click on this link https://tell.gao.gov/traguide to provide us with comments on the Guide.

If you have any questions concerning the Guide, you may contact Dr. Timothy Persons at (202) 512-3000 or personst@gao.gov, or Mike Sullivan at (202) 512-4841 or sullivanm@gao.gov. Contact points for GAO's Office of Congressional Relations and Office of Public Affairs may be found on the last page of this Guide.

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Introduction

Technology readiness assessments (TRA)—evaluations used to determine a technology's maturity—have been used widely at the U.S. Department of Defense (DOD) and National Aeronautics and Space Administration (NASA) since the early 2000s. Other government agencies, as well as industries in aerospace, maritime, oil and gas, electronics, and heavy equipment have also used TRAs to help manage their acquisitions. Few agencies have guides for assessing a technology's maturity and its readiness for integration into larger acquisition programs, and the federal government has not adopted a generally accepted approach for evaluating technology beyond using technology readiness level (TRL) measures.[2] This TRA Guide (referred to as the Guide) is intended to help fill those gaps.

The Guide has two purposes: (1) describe generally accepted best practices for conducting effective evaluations of technology developed for systems or acquisition programs, and (2) provide program managers, technology developers, and governance bodies with the tools they need to more effectively mature technology, determine its readiness, and manage and mitigate risk.[3] In addition, oversight bodies—such as those with department or agency acquisition officials or government auditors—may use the Guide to evaluate whether the fundamental principles and practices of effective TRAs are followed along with the credibility, objectivity, reliability, and usefulness of those assessments.

The Guide recognizes that TRAs have different customers within an organization, such as the governance body charged with program oversight in managing and allocating fiscal resources as the gatekeeper, as well as a more narrow audience, such as the program manager, technology developer, or independent consultant that uses them to determine progress in achieving technical maturity. The Guide discusses TRAs in context of the full range of best practices to be used for governance, but also provides information on where

[2] TRLs are a scale of nine levels used to measure a technology's progress, starting with paper studies of a basic concept and ending with a technology that has proven itself in actual usage on the product.

[3] TRAs do not assess the risk associated with the technical maturity of a technology or system. Rather they identify specific risks (e.g., performance data gaps) associated with the specific technologies, which provides a basis for quantifying those risks through formal risk assessments. Similarly, the Technology Maturation Plan resulting from a TRA, described in Chapter 9, provides the basis for appropriate risk mitigation actions.

certain steps may be tailored for assessments for the narrower audience, referred herein as knowledge building TRAs.

The Guide's chapters first introduce the concept of technology readiness assessment, its basis in government and commercial best practices for product and systems development, and the benefits a program, agency, or organization might expect to gain from conducting them. It then identifies best practices for organizing and executing TRAs. Specific chapters are devoted to the overall TRA process, designing a technology maturity strategy and plan and assembling a team, identifying and evaluating critical technologies, reporting and using evidence-based results. These chapters are followed by a discussion of technology maturation plans (TMPs) which build on the TRA findings and describe the steps needed to proceed to higher levels of technology readiness. Further chapters discuss the current state of practices related to the readiness of software embedded technologies and tools for evaluating system-level readiness, which is an extension of the concept of technology readiness. Further, the Guide maps best practices to the characteristics of effective TRAs, which include credibility, objectivity, reliability, and usefulness.

The Guide draws heavily from DOD, NASA, and the Department of Energy (DOE) for best practices, terminology, and examples. In addition, the Guide draws from credible resources, materials, and tools developed and applied by experts and organizations in order to capture the current thinking on technology readiness and maturity. Existing government agency guidance is largely geared toward the conduct of TRAs to support major acquisition decisions, in particular the decision to authorize the start of product or system development and allocation of substantial resources. Demonstrating that a program's critical technologies have been proven to work in their intended operational environment before making a commitment to product development has also been the focus of GAO's work on technology readiness since the late 1990s.

While the focus of this Guide and the best practices it describes is on how to conduct credible TRAs from the start of technology development to help plan technology maturation efforts and before product development decisions, the expert community has recognized that more frequent, regular assessments of the maturity of a project's or program's critical technologies are also best practices for technology and program management. However, some experts have been concerned that applying the same set of practices to these more frequent assessments might make them too time consuming and cost prohibitive and ultimately dissuade technology and program managers from conducting them. To that end, the Guide emphasizes that best practices for conducting TRAs can in some cases be tailored and routinely applied to meet specific program goals. These goals range from increasing the knowledge of program managers to better understanding transition risks when maturing technologies to demonstrating readiness for full-scale product development, production, or deployment to a governance body at a decision point.

One such example of a tailored approach is through project self-assessments referred herein as knowledge-building TRAs, as part of peer reviews, against the technology maturation planning efforts. In the case of transition to full-scale product development, a decision maker would want to ensure that the entire range of best practices has been followed to evaluate technology readiness before making a major commitment of resources.

The Guide's Case Studies

To augment the text, the Guide contains a number of case studies drawn from GAO reviews. These case studies highlight problems typically associated with technology development efforts and augment the main points and lessons learned that the material in the chapters covers. For example, GAO has found that in many programs, cost growth and schedule delays resulted from overly optimistic assumptions about technology maturity. Experts have also found that many program managers and technology developers suffer from the assumption that they can deliver state-of-the-art technology upgrades within a constrained budget before evidence is available that the technology will perform as expected in the environment for which it is planned. Appendix II has a list of auditing agencies and their websites. Appendix III has additional background information for each program used in the case studies. GAO would welcome additional case studies from TRA practitioners as part of the public comment process.

The Guide's Readers

The primary audiences for this Guide are the organizations and the program managers and technology developers who rely on and develop technology for acquisition programs, the governance bodies who oversee acquisition efforts and make important decisions about the commitment of organizational resources, the contractors that develop technology, and the audit community that evaluates these efforts. Organizations that do not have formal policies for conducting or reviewing TRAs will benefit from the Guide because it will inform them of the criteria GAO may use in evaluating their programs. In addition to GAO, other audit organizations including Inspectors General may also use the criteria prescribed in the Guide for their work. It may help ease the burden on agencies as they work to meet the needs of various oversight offices and should help speed and facilitate the delivery of data request items. We intend to periodically update the Guide. Comments and suggestions from experienced users as well as recommendations from experts in the relevant fields are welcome.

Acknowledgments

GAO thanks the many members of the technology readiness assessment community who helped make the Guide a reality. After we discussed our conceptual plan to embark on this effort to develop a government-wide guide, experts from across the federal government, commercial industry, nonprofits, and academia expressed interest in working with us. From our first kick-off meeting in January 2013 forward, their contributions have been invaluable. Together with these experts, GAO has developed a Guide that outlines the best practices and key characteristics of effective TRAs and promotes their use as a knowledge building exercise that can benefit many agencies in the federal government as well as organizations abroad. We would like to thank everyone who gave their time, attended meetings, provided valuable documentation, and responded to requests for comments. Those who worked with us on this Guide are listed in appendix IV. Additional contacts and acknowledgments are in appendix V.

Chapter 1

What Is a Technology Readiness Assessment (TRA)?

A technology readiness assessment (TRA) is an evaluation of the maturity of critical elements of a product's technologies, often called critical technologies. It is a normal outgrowth of the system engineering process and relies on data generated during the course of technology or system development. The TRA frequently uses a maturity scale—technology readiness levels (TRLs)—that are ordered according to the characteristics of the demonstration or testing environment under which a given technology was tested at defined points in time. The scale consists of nine levels, each one requiring the technology to be demonstrated in incrementally higher levels of fidelity in terms of its form, the level of integration with other parts of the system, and its operating environment than the previous, until at the final level the technology is described in terms of actual system performance in an operational environment.

An evaluation can be conducted and updated with regular frequency throughout the acquisition cycle, and there is no pre-determined number of evaluations or time intervals for conducting these evaluations. Similarly, it is not a requirement that each evaluation comprehensively consider all critical technologies. Rather, the key consideration is that each critical technology should be evaluated during development. While the TRA does not measure or assign a risk level to a project or assess the ability to achieve system cost, schedule or performance goals, it is a fundamental means for evaluating an important component of risk—the maturity of technology and its readiness or ability to perform as part of a larger system. The TRA process is a risk identification tool that will help to highlight critical technology maturity concerns.

GAO has found that the readiness of critical technologies at the start of system development affects the schedule and cost of developing a product.[4] Therefore, a TRA performed before development begins is an important management information tool for both the product managers responsible for the daily management of developing a product and the governance bodies charged with the oversight of an acquisition program.

[4]See GAO-09-3SP, GAO-12-120G, and GAO, *Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes*, GAO/NSIAD-99-162 (Washington, D.C.: July 1999).

Definitions and Overview

In describing TRAs, it is necessary to understand the measures most commonly used for an assessment—the TRLs, a compendium of characteristics describing increasing levels of technical maturity based on demonstrations of capabilities. The performance of a technology is compared to definitions of maturity numbered 1-9 based on demonstrations of increasing levels of fidelity and complexity.

Experts agree that TRLs are the most common measure for systematically communicating the readiness of new technologies or new applications of existing technologies to be incorporated into a product. Other readiness level measures (for example manufacturing readiness levels) have been proposed with varying degrees of success and use throughout the lifecycle of a program.[5] Although not exhaustive, appendix VII lists and describes other types of readiness levels.

Government agencies and other organizations commonly use TRLs to describe the maturity of a given technology within its development life-cycle. Some organizations have tailored the TRL definitions to suit their product development applications; but, in general, TRLs are measured along a 1-9 scale, starting with level 1 paper studies of the basic concept, moving to laboratory demonstrations around level 4, and ending at level 9, where the technology is tested and proven, integrated into a product, and successfully operated in its intended environment. Figure 1 includes the nine TRL levels and descriptions DOD, NASA, and other organizations use. Appendix VI has additional examples of government agencies' TRL definitions and descriptions, including those for both hardware and software.

[5] GAO, *Best Practices: DOD Can Achieve Better Outcomes by Standardizing the Way Manufacturing Risks are Managed*, GAO-10-439 (Washington, D.C.: Apr. 22, 2010).

Figure 1: Technology Readiness Levels

Technology readiness level (TRL)		Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in 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.
5	Component and/or breadboard validation in 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.
6	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 its 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.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8	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.
9	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 operational test and evaluation. Examples include using the system under operational mission conditions.

Source: GAO simplification of agency documents. | GAO-16-410G

TRAs Inform Technology Development and Identify Potential Concerns

While a TRA uses TRLs as key metrics for evaluation of each technology, an assessment is more than just a single number at only single points in time. It is a compilation of lower-level assessments that could span several years, based on the program schedule and complexity of the development. Evaluations can help gauge the progress of technology development, inform program plans, and identify potential concerns for decision makers throughout acquisitions. Conducting TRAs periodically and during the earlier phases of development can identify potential concerns before risks are carried into the later and more expensive stages of system development. TRAs can also facilitate communication between technology developers, program managers, and acquisition officials throughout development and at key decision points by providing a common language for discussing technology readiness and related technical risks. Finally, TRA results can inform other assessments and planning activities, such as cost and schedule estimates, risk assessments, and technology maturation plans.

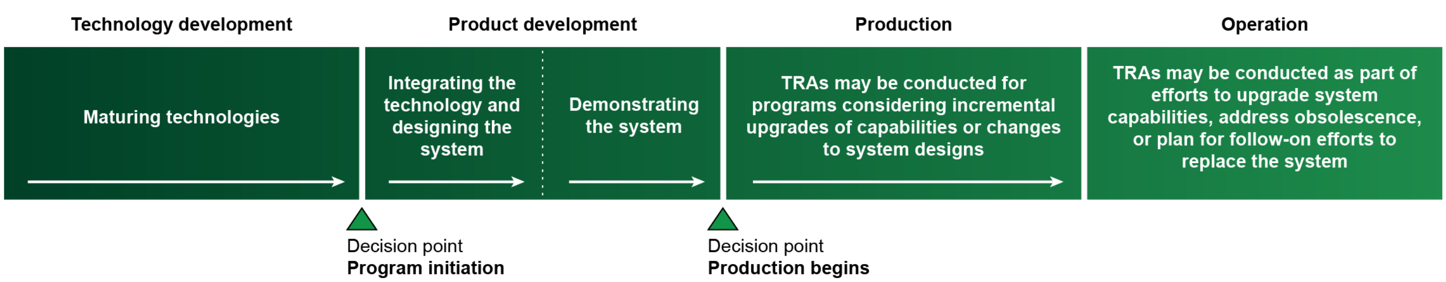
Overview of Technology Development and Its Relationship to Acquisition Programs

Acquisition programs and projects in many organizations are broadly divided into phases of technology development, product design, production, and operational activities. These phases may be divided by decision points or stage gates with criteria and activities that should be met or completed before committing additional resources to the project. Passing from one decision point to the next requires evidence and documentation such as test reports, analysis, and other assessments to demonstrate that these criteria have been met. During the acquisition life cycle, TRAs can be used to monitor the progress of maturing technologies and to determine how ready a technology is to make a transition from technology development to subsequent phases.

In addition to TRAs, organizations use other types of assessments and reviews to examine the technical aspects of acquisition. For example, systems engineering reviews are used to examine the integration of components into systems, test reports are used to detail the outcomes of developmental tests, and manufacturing readiness assessments are used to examine the maturity of the processes that will be applied to manufacture the product.[6] Each of these reviews provides incremental knowledge during the course of a program and helps managers assess how well a project is progressing. Taken together, the different kinds of reviews and assessments develop a picture of how the project is proceeding and may highlight risk areas.

The Guide focuses on strategies that begin with an innovative solution to a set of needs and requirements that must integrate technologies of varying maturity levels into a product. Therefore, acquisitions considered here have their origin in a set of performance requirements requiring a materiel solution. These solutions often require some technology development as well as requirements to integrate with other systems as part of the acquisition process. This technology development may involve new invention, technology maturation, or the adaptation of existing technologies for new applications or environments. Figure 2 depicts a four-phased acquisition process: technology development, product development, production, and operations. When examining this process more closely, each broad phase may contain a number of activities designed to increase knowledge about the technologies and product being developed, built, and eventually operated. Each phase has a transition to the next with a documented evidence-based review that demonstrates the knowledge gained during the phase and demonstrates the progress in development compared to goals and exit criteria established for the phase.

Figure 2: Phased Acquisition Cycle with Decision Points



Source: GAO simplification of agency documents. | GAO-16-410G

[6]For some applications, such as development of complex chemical processing facilities, validation of the performance of all of the technology elements (TEs), including critical technologies, in an integrated system is crucial to the technology maturation process. As such, assessment of the integrated processing system must be completed as part of key TRAs.

Since each phase comprises multiple activities, the acquisition cycle may be further divided into “decision points” or “stage gates” where activities are focused on a narrower developmental task than those encompassed by an entire phase. For example, during the technology development phase, one stage may focus on exploring technologies and a subsequent stage may be concerned with maturing selected technologies; a third stage could consist of activities to help in the transition to mature technologies in the product development phase. A decision point at the end of the transition gate would signal the start of product development. The figure is notional since each organization creates a model that fits the specific types of acquisition processes they use.

It is important to point out that within the phased acquisition cycle, TRAs are not typically conducted in the later production or operation phases. However, during the production phase TRAs may have value for programs that are considering incremental upgrades of capabilities or changes to system designs to address issues such as parts obsolescence. In addition, TRAs may also be conducted during the operation phase as part of efforts to upgrade system capabilities, address obsolescence, or plan for follow-on efforts to eventually replace the system.

The following brief descriptions highlight characteristics of each phase and the potential role of TRAs within them.

Technology Development

In the technology development phase, even before a product use for a technology is defined, the science and technology community explores available technologies (conceptual systems, components, or enabling technology areas) and matures them to a stage that facilitates their integration into a product as part of a formal acquisition program, typically at the point when the technology reaches a TRL 6 or 7. Technology development is a continuous discovery and development process reflecting close collaboration between the science and technology community, the user, and the system developer. It is iterative, designed to assess the viability of technologies while refining user requirements. The management and mitigation of technology and technology integration risk, which allows less costly and less time-consuming systems development, are a crucial part of overall program management and are especially relevant to meeting cost and schedule goals.

Technology developed in science and technology programs or procured from industry or other sources should be demonstrated in a relevant environment (TRL 6), preferably in an operational environment (TRL 7), such that it is considered mature enough to use for product development. TRAs should be conducted as independent assessments to determine maturity. If technology is not mature, the program should either consider using alternative technology that is mature and that can meet the user's needs or should engage the user in a dialogue on appropriately modifying the requirements. It is important to point out that agencies approach alternative technologies in different ways. For example, some agencies conduct an analysis of alternatives to identify the most mature, cost-effective technologies, using a tailored TRA process to select the technology elements that constitute a system. If there are technologies that can perform similar functions that are at similar TRLs, and require technology maturation and additional performance data, parallel technology development and testing is often used in the early stages to develop the data required to make the final selection. In this phase, regular assessments of technology progress provide confidence to the product developers that the technology is advancing the readiness to function in a product within available resources of time and funding. Evidence-based documentation may include multiple TRAs that can inform analyses of alternative solutions, baseline technology strategy, gauge the progress of development efforts, and establish or update maturation plans to increase the likelihood for successful transition of technology into product development.[7]

Product Development

Product development can be characterized as the further reduction of technology risk, especially as it relates to the integration of technologies into a product or system design. Ideally product development begins with the transition of mature technologies to the project developer or program and ends when the product design is complete and developmental testing has shown that the various components can work together as an integrated whole and can be manufactured and sustained within established cost, schedule, and quality goals. Product development activities include the continued maturation of technologies if needed, development and refinement of the design including the preparation of detailed design drawings, construction of higher fidelity prototypes of components and systems, integration activities to ensure that the components work together, testing to ensure that performance and reliability

[7] Tailored, informal TRAs are often used to support formal analysis of alternatives efforts. Various agencies recognize that tailored knowledge building self-assessment TRAs are cost-effective and useful tools for informing the technology maturation process, which helps limit the more resource-intensive formal, independent TRAs to key project milestones or stage gates.

expectations can be met, and demonstrations of manufacturing capabilities to show that the product can be consistently produced within cost, schedule, assessment of sustainability through the lifecycle of the product, and quality and performance goals. Product development may be the last phase for organizations such as NASA who may build a single product where there is no production of multiple units.

TRAs serve a useful purpose during this phase to ensure that the technologies are fully mature before proceeding into production—that is the technologies have been demonstrated as an integrated system in an operational environment and are likely to meet key performance requirements.[8] Upon entering product development and therefore having achieved at least TRL 6 (system demonstration in a relevant environment) the critical technology is at the point that it is considered beyond the reliance of science and technology investment and is dependent on standard systems engineering development practices to achieve a fully mature status expected for eventual production. During the product development process, TRAs are important inputs into systems engineering events, such as a project's critical design review, and can expose knowledge gaps. If a project has low TRLs (i.e., less than TRL 6) at this point, then the project does not have a solid technical basis on which to develop its design and it could be put itself at risk approving a design that is less likely to remain stable.

Production

The beginning of the production phase marks a point at which the elements of a product—its technologies and design—are sufficiently mature. Manufactured items are subjected to acceptance testing designed to ensure that the manufactured products are maintaining quality standards, before they are placed in the inventory. During this period, production processes are under statistical control and used to ensure the product has attained sufficient reliability and can be produced at an efficient rate within cost and quality goals. Depending on quantities to be produced, production may span 10 years or more.

[8] For some applications, extended factory acceptance testing, which can include integrated testing of the actual components to be placed into service, is used as part of the technology maturation process and overall risk mitigation strategy.

TRAs are not typically conducted during this phase, although they may have value for programs considering incremental upgrades of capabilities or changes to system designs to address issues such as parts obsolescence.

Operation

The operation phase marks the period of the active use of a product. Organizations may subject the product to follow-on operational testing or to inspections to ensure it is performing as designed. Operational time periods vary, depending on the maturity of the products and their average useful life. The useful life of a product is determined by its use and by its materials. Buildings such as containment facilities may have a 30-year life. Military equipment is routinely projected to have a 15-30 year life-cycle. Systems designed for scientific investigation may have life cycles that may run from 5-15 years. During the operational phase, products are maintained and may undergo refurbishing or receive upgrades. Obsolescence of technologies (that is, organizations find it too costly or infeasible to maintain old technology) is an important factor as is continued supply of the production components, including spare parts and replenishments.

Similar to the production phase, TRAs may be conducted during the operations phase as part of efforts to upgrade system capabilities, address obsolescence, or plan for follow-on efforts to eventually replace the system.

Technology Development Models

Not every project develops a unique product to meet identified needs. Organizations develop new products and establish new programs, but they also undertake other work, such as upgrades to existing products or modifications to products developed by commercial vendors, adjusting the products to meet agency standards or needs. If the project is incrementally developing a product to fill emerging needs, the product may meet minimum requirements but not the desired end state. Successive iterations of development bring the product design to its full capability.

In the case of incremental development or evolutionary acquisition, each product iteration depends on the availability of mature technologies. This may entail successive technology development phases. Program strategies, such as block upgrades, pre-planned product improvements, and similar efforts that provide a significant increase in operational capability, may be managed as separate increments.[9] In an evolutionary acquisition, identifying and developing the technologies necessary for follow-on increments continue in parallel with the acquisition of preceding increments, allowing the mature technologies to more rapidly proceed into the product development phase. TRAs can play an important role in informing the timing of incremental upgrades by providing information on whether the technologies are mature and ready to be integrated onto a product.

TRA's Relationship to Program Management and Oversight

When planned and executed well, TRAs are complementary to existing program management, system development, and oversight and governance practices. Many practices needed to produce a TRA will be a natural outgrowth of sound systems engineering practices, such as the identification of critical technologies, creation of a detailed systems structure and a plan for ensuring that critical technologies are evaluated and that evidence of the evaluation and the results are retained both for proof that the processes were undertaken and for evidence of progress toward maturity. TRA data collection efforts may be incorporated as an integral part of systems engineering and processes upfront and throughout the development and acquisition of a program. The program manager for the government and for the contractor, both the internal project management and engineering teams, as well as technology developers, will use these documents to inform the management of the program and track its progress.

Programs are also subject to periodic oversight from governance officials and other decision makers who have responsibility for ensuring that acquisitions are progressing suitably and ready to move forward past key decision points. For these meetings and decision points, TRAs provide evidence that the product's technical development is progressing as desired and that technologies are mature enough to move to the next phase of development. If program managers have conducted multiple TRAs as needed to help inform their management of the technology development process, then they have already incrementally built a knowledge base that can provide persuasive evidence that the developers have been diligent and thorough in their examination of the critical technologies and that the technologies themselves have matured at a pace commensurate with the acquisition phases of the program. In this case,

[9] An incremental increase in operational capability developed based on mature technology and delivered to the user in a useful grouping.

governance requirements might be met by validating a program's existing body of TRA knowledge rather than conducting a new assessment.

Tailoring TRAs for Different Purposes

The TRA process and the content of a TRA can be tailored depending on the purpose and audience for which it is conducted. While the focus of this Guide and the best practices it describes is on how to conduct credible TRAs from the start of technology development to help plan technology maturation efforts and before product development decisions, the expert community has recognized that more frequent, regular assessments of the maturity of a project's or program's critical technologies are also best practices for technology and program management. However, some experts have been concerned that applying the same set of practices to these more frequent assessments might make them too time consuming and cost prohibitive and ultimately dissuade technology and program managers from conducting them.

One such example of a tailored approach is through project self-assessments referred herein as knowledge-building TRAs, as part of peer reviews, against the technology maturation efforts. These types of TRAs might be conducted by or for a narrow audience—the program manager or systems engineer—to calculate progress in achieving technical maturity for a specific technology or group of technologies. They may also lack the rigor that might be associated with TRAs conducted to support a major decision point or stage gate review.

Tailoring the TRA process might not be appropriate in other situations. In the case of transition to full-scale product development, a decision maker would want to ensure that the entire range of best practices has been followed to evaluate technology readiness before making a major commitment of resources.

Chapter 2

Why TRAs Are Important and Understanding Their Limitations

More than 15 years ago, GAO has shown that a disciplined and knowledge-based approach in evaluating technology was fundamental in putting acquisition programs in a better position to succeed. In 1999, GAO published Best Practices: Better Management of Technology Can Improve Weapon System Outcomes, reporting that maturing new technology before it is included in a product is perhaps the most important determinant of the success of the eventual product.[10] In that report, GAO found that incorporating immature technologies into products increases the likelihood of cost overruns and delays in product development.

GAO found that when program managers and technology developers had the support of disciplined processes, employed a knowledge-based approach throughout acquisitions, and had access to readily available information and readiness standards, it helped them to safeguard product development from undue technology risks. In fact, technology experts agree that when those conducting TRAs follow a disciplined and repeatable process, focus on how the end user plans to employ the technology, and rely on sufficient evidence to produce a credible TRA report, program managers, technology developers and governance bodies are in a better position to make informed decisions.

High quality evidence-based TRAs provide managers and governance bodies with important information for making technical and resource allocation decisions on whether a technology or system is sufficiently mature to move past a decision point to the next acquisition phase, needs additional work, or should be discontinued or reconsidered in favor of more promising technology. The TRA results—in the form of a TRA report—also serve as input to other program management decisions to estimate cost, schedule, and risk. Importantly, TRAs provide a common language and framework or reference point to facilitate dialogue supported by well-defined metrics and methods across organizational disciplines, departments, and business functions. In doing so, they serve as a basis for addressing transition issues, solidifying stakeholder commitments, and identifying potential concerns that may require closer examination in order to track and monitor them or to develop plans to mitigate potential risks, such as

[10] GAO/NSIAD-99-162.

preparing a technology maturation plan (TMP) for immature technologies.[11] There are other supplemental analysis methods available that rely on the results of TRAs to help estimate the level of effort needed to mature the technology.[12]

It is worth noting that commercial organizations may use TRAs to gauge their own internal investments such as research and development projects that have the potential for use on future government contracts. For example, Raytheon Space and Airborne Systems uses TRAs as a way to ensure that investments in their internal and customer funded research projects are advancing technology development efforts to the appropriate stage and at the right rate to achieve key goals or acquisition milestones. Raytheon believes that evaluating promising technologies and aligning them with DOD efforts can put them in a more competitive position. Raytheon developed the following tailored process to follow many of DOD's steps that include:

- Identifying potential systems and programs as likely recipients of the technology.
- Using the research team to perform the TRA, supplemented when necessary by internal technology readiness experts.
- Reviewing assessments by subject matter experts in technology, technology readiness, and business leaders to ensure both accuracy of the assessment and adequate progression of the technology.

[11]The TMP is developed for critical technologies that do not meet specific TRL goals or expectations where gaps exist that require further evaluation, testing or engineering work in order to bring the immature technology to the appropriate maturity level. As a best practice, the plan identifies the activities needed to bring immature critical technology up to a desired TRL. The plan is updated periodically when subsequent TRAs are conducted to determine technology progress or maturity, whether it has met expectations or goals, and whether the immaturity concerns, risks, or issues have been satisfactorily addressed or resolved.

[12]The Advancement Degree of Difficulty (AD2) is a method that predicts what is required to move a technology component, subsystem, or system from one TRL to another. Information is provided by determining (1) the activities required to mature the technology (2) the cost associated with those activities, (3) the time required to accomplish those activities, and (4) the likelihood that those activities cannot be accomplished. The information is derived from a set of questions in the five areas of design and analysis, manufacturing, software development, test, and operations. Not all agencies use a standardized AD2 process. Some agencies rely on development of the TMP to identify developmental tasks and quantify the resources related to maturing a critical technology from its current TRL to the target TRL. Another method, Research and Development Degree of Difficulty (R&D3) is a 5-level scale intended to supplement the TRL by characterizing the degree of difficulty in proceeding from the current TRL state to desired level, with 5 being very difficult a 1 being least difficult to mature the technology (Mankins 2002).The Risk Identification, Integration, and Ilities (RI3) method to support program managers and system engineers in the development and integration of new and reused technologies by identifying technical risks that historically have hampered previous programs. When used as an integral part of an integrated systems engineering strategy, this approach can be done early to enable evidence-based decisions and mitigate the potential for cost overruns and schedule delays.

- Relying on mechanisms to change the research plan to accelerate or retard the development based upon the technical readiness assessment.
- Ensuring objectivity in the assessment—particularly with regard to demonstration environments—necessitated by system requirement evolution. That is, since investments must precede exact system requirements, practitioners must be flexible and forward thinking in order to hit a "moving target."

Maturity of Technology at Program Start Is an Important Determinant of Success

TRLs have proven to be reliable indicators of the relative maturity of the technologies reviewed, both commercial and military, and their eventual success after they were included in product development programs. In GAO's 1999 report, Best Practices: Better Management of Technology Can Improve Weapon System Outcomes, DOD and commercial technology development cases showed that demonstrating a high level of maturity before allowing new technologies into product development programs put those programs in a better position to succeed. Simply put, the more mature technology is at the start of the program, the more likely the program will succeed in meeting its objectives. Technologies that were included in a product development before they were mature later contributed to cost increases and schedule delays in those products (see table 1).

Table 1: Cost and Schedule Experiences for Products with Mature and Immature Technologies

Product development			
Product development and associated technologies	TRL at program initiation	Cost growth	Schedule delay
Comanche helicopter			
Engine	5		
Rotor	5		
Forward looking infrared	3		
Helmet mounted display	3		
Integrated avionics	3	101 percent[a]	120 percent[a]
Brilliant Anti-Armor submunition			
Acoustic sensor	2		
Infrared seeker	3		
Warhead	3		
Inertial measurement unit	3		
Data processors	3	88 percent	62 percent
Hughes HS-702 satellite			
Solar cell array	6	None	None
Ford Jaguar automobile			
Adaptive cruise control	8		
Voice activated controls	8	None	None

Source: GAO/NSIAD-99-162

[a]The Comanche, in particular, has experienced a great deal of cost growth and schedule slippage for many reasons, of which technology immaturity is only one. Other factors, such as changing the scope, funding, and pace of the program for affordability reasons, have also contributed.

TRA Process Is a Mechanism That Informs Important Acquisition Functions

In developing this Guide, technology experts, managers, and practitioners agreed that conducting TRAs provides many tangible benefits in addition to an evaluation of the maturity of critical technologies at a given time. For example, TRAs can be used to protect program managers from unknowingly accepting or being forced to accept immature technologies into their programs. Executing the TRA process includes a multitude of activities that require practitioners to cross organizational, professional, and managerial boundaries to establish lines of communication, exchange information, and keep scientists, systems engineers, acquisition officials, and others informed throughout the development of a program or project. These activities increases knowledge and facilitate understanding of how technologies interact with one another and with the larger systems or programs that integrate them. They also increase awareness of changes that could affect other elements and systems, while eliciting involvement and participation of the test and evaluation communities to ensure that maturity demonstrations adequately stress technologies appropriate to the expected relevant or operational environment. Programs that forgo TRAs or ignore the information they provide risk negative consequences in terms of cost increases, schedule delays, or delivering less capability than promised.

The TRA process is one mechanism that identifies potential risks during early technology development before they are carried past a decision point and into product development, where resource requirements are often substantial. Case study 1 shows how programs can be affected when technologies critical to development of a program—that should have been "mature" at program initiation, and well before the program entered the product phase—are actually immature.

Case Study 1: Immature Technologies Increase Risk, from *DOD,* GAO-08-408

Before its cancellation in 2011, the Future Combat Systems—comprised of 14 weapon systems and an advanced information network—was the centerpiece of the Army's effort to transition to a lighter, more agile, and more capable combat force. In March 2008, GAO has shown that 42 out of the program's 44 critical technologies had not reached maturity halfway through its development schedule and budget at five years and $12 billion in spending. Major technical challenges, the Army's acquisition strategy, and the cost of the program, as well as insufficient oversight and review, all contributed to its subsequent cancellation.

GAO*, Defense Acquisitions: 2009 Is a Critical Juncture for the Army's Future Combat System,* GAO-08-408 (Washington, D.C.: March 7, 2008).

Case study 2 shows how the absence of key information about the maturity of critical technologies can hinder important decisions.

Case Study 2: Assessments Provide Key Information, from *DOE*, GAO-10-675

In June 2010, GAO has shown that the Department of Energy (DOE) was unable to provide information to policymakers on the progress of two key technologies to reduce carbon dioxide emissions. Essentially, DOE did not systematically assess the maturity or use a standard set of benchmarks or terms to report on the maturity of technologies. When policymakers were determining climate change policies, these shortcomings limited their oversight in DOE's spending to develop these technologies such as determining future resource needs to commercially deploy these technologies. GAO recommended that DOE develop a set of standard benchmarks to measure and report to Congress on the maturity of the two key technologies to address information gaps and technology development issues.

GAO*, Coal Power Plants: Opportunities Exist for DOE to Provide Better Information on the Maturity of Key Technologies to Reduce Carbon Dioxide Emission,* GAO-10-675 (Washington, D.C.: June 16, 2010).

Understanding TRAs Can Help Practitioners and Consumers of Information

TRAs provide valuable information that can help program managers, technology developers, and governance bodies make informed decisions, but they also have inherent limitations that can pose challenges in how they are designed and applied and how decision makers interpret the results. Understanding these important characteristics can help both practitioners and those who depend on TRA information to better understand context in terms of what is being assessed, how to consider them in light of other development and integration efforts, what the information does and does not convey, and how to apply the best practices in this Guide. Figure 3 describes the TRA and TRL limitations based on research and expert input collected during the development of this Guide.

Figure 3: Technology Readiness Assessment and Technology Readiness Level Limitations

Limitation of TRAs and TRLs	Description
Limited shelf life	The TRL maturity rating is a snapshot in time with a limited shelf life. It is not predictive nor an estimation of future outcomes. As technology advances and matures, TRAs also evolve and decay with time.
One size fits all approach is not feasible	Hardware and software technology vary in complexity, size, and property (physical and/or abstract) thereby making it sometimes difficult to scope the TRA, collect relevant information and artifacts necessary to render a credible opinion, and identify and assess critical technologies. Each technology may be unique and the TRA may require tailoring specific to the technologies being evaluated.
Subject to the availability and makeup of the assessment team lead and its members	Availability of assessment team with the necessary expertise may be limited or personnel may be in short supply in some organizations, disciplines, or industries. The assessment team lead and members must possess the appropriate expertise, knowledge, and TRA training to prepare, execute, and apply TRA best practices.
Subject to interpretation, experience, culture, or organizational bias	Each organization involved in the development and maturation of technologies has its own culture, perspective, expectation, or bias that can influence how technology is viewed, assessed, and observed. This influences how the TRA results may be interpreted, and/or acted upon. Anecdotal reports suggest that managers and developers have influenced the TRA results because of other program goals, budget pressures, or other expectations.
Evidence used to render professional opinion is only as good as the artifacts, analyses, test reports, and relevant important information provided and relied upon	Artifacts, data, and information collected to evaluate critical technologies may have dependencies, functions, and interactions with other program elements that may be outside the scope of the assessment. Such essential artifacts could affect the assessment and careful consideration of these should be part of the TRA design and execution. Changes in requirements, technology designs, or other elements during development can also affect the assessment.
TRL metric is ordinal	The TRL metrics used to convey technology maturity are ordinal, but maturing technology along the TRL scale is not consistent. For example, moving a technology from a TRL 3 to a TRL 4 may not require the same amount of effort as moving the same technology from a TRL 6 to a TRL 7.

Source: GAO analysis and subject matter expert input. | GAO-16-410G

TRAs Are Snapshots in Time

TRAs are point in time evaluations of a technology development effort or acquisition program that provide a snapshot of how a critical technology has been demonstrated by a certain point in its development. While there is no standard guideline for the shelf life of a TRA rating, experts assert that it can range anywhere from 1 to 6 months, depending on the type of technology and how rapidly it evolves. While a TRA may determine the maturity of a technology, it does not in and of itself inform the developer or manager what is required to successfully complete its development. Indeed, the amount of effort to advance to a higher TRL not only differs largely between TRLs but also may not increase linearly between progressively higher TRLs. Because TRAs are limited in terms of what is evaluated and what the information provides, practitioners and experts have established other program management tools to augment technology maturation and the decision making process.

Advancements in Technology Can Pose Challenges in Applying TRAs

With unprecedented advancements in technology and greater use of software in providing key functionality for new systems, identifying and evaluating critical technologies have become more challenging. In fact, many experts do not agree on the definition of technology itself. Nowhere is this truer than in the military where DOD wants to integrate and better manage the technology and software that play an ever-increasing role in modern weapons systems and national security. In addition, NASA space missions are more ambitious and require the development and integration of more advanced and complex scientific instruments and vehicles than ever before. Hardware systems embedded with software challenge traditional ways of viewing and evaluating critical technology. [13] The issues include a lack of distinction among software types (newly developed, reused, and commercial-off-the-shelf), insufficient experience and knowledge when moving from the laboratory to a “relevant” environment, poor oversight during development, and inconsistent definitions of what represents new

[13]Embedded software is a type of software that is built into hardware systems. This software is typically designed to perform one specific function, although a single piece of hardware may contain multiple pieces of software embedded in it. Any piece of technology that has circuit boards and computer chips will likely have embedded software within it, from digital clocks to cell phones to calculators. These systems allow many of the advanced functions that are common in modern devices.

software technology. In addition, in some cases, it is no longer possible to evaluate the maturity of certain hardware technologies without their embedded software.

Urgent needs to develop, deliver, and integrate technologies in less time have also challenged organizations in the way they evaluate technology maturity and risks. For example, gaps in military capabilities on the battlefield mean that mature technologies must be developed and integrated into systems more rapidly to address life threatening situations. Likewise, rapid advances in methods to respond to public healthcare concerns mean that the Food and Drug Administration must evaluate the maturity of technology and systems to ensure that certain criteria and levels of maturity have been achieved before they can be approved. Often times, these urgent needs create pressure for organizations and their program managers to take greater risks or to short circuit the process for evaluating the maturity of critical technologies.

Today’s knowledge base is evolving about what information program managers and technology developers need to understand the risks where software is involved. Moreover, technologies, such as software-only or space systems create inherent limitations in evaluating them because they have no physical property or their operational environments are not easily replicated for test purposes. Likewise, large information technology (IT) systems of highly distributed computer networks, systems, and servers on a national or global scale create challenges on how to realistically identify what a critical technology is and how to feasibly scope the TRA.

In addition, TRAs generally focus on a particular technology or set of technologies identified as critical to the operation of a subsystem, system, or larger capital acquisition program. Although the TRA is an evaluation of the technology and software itself, critical technologies today often function with more systems and subsystems than they did in the previous decades. Therefore, conducting TRAs in context of the interaction with other systems and subsystems has become additionally complex.

Organizational Experience, Culture, and Bias Can Affect TRAs

Organizational communities that create, develop, manage, produce, and integrate technology are diverse and each has their own set of objectives, goals, and missions. Differences between them can lead to different perspectives in planning and conducting TRAs and interpreting the results. Terms used and what they mean often differ. For example, terms like “simulated environment,” “relevant environment,” and “operational environment” often have different meanings for different organizations, disciplines, and business functions. Therefore, the quality of a TRA depends on close communication among all the stakeholders, including the technology developer, program manager, governance body, and assessment team that performs the evaluation.

Optimism, which is pervasive in acquisition programs, can also affect TRA results or their interpretation. For example, program managers may believe that lessons learned from past programs will benefit their program and assumptions about the maturity of certain technologies may not be closely scrutinized. Or, they may be more willing to take on greater risk and accept immature technology because their promised performance is vital to obtaining funding and stakeholder buy-in. In addition, in today’s competitive environment, contractor program managers may be overly optimistic about the maturity of critical technologies, especially prior to contract award. Case study 3 highlights that underestimating the cost to mature critical technologies can negatively affect program development and schedule.

Case Study 3: Space Programs Often Underestimate Costs, from *DOD*, GAO-07-96

Costs for DOD space acquisitions have been consistently underestimated over the past several decades—sometimes by billions of dollars. In 2006, GAO has shown that cost growth in DOD space programs was largely caused by initiating programs before determining whether requirements were achievable within available resources. Unrealistic cost estimates resulted in shifting funds to and from programs, which also exacerbated agencywide space acquisition problems. For example, on the National Polar-orbiting Operational Environmental Satellite System program, DOD and the Department of Commerce committed to the development and production of satellites before the technology was mature—only 1 of 14 critical technologies was mature at program initiation, and 1 technology was found to be less mature after the contractor conducted more verification testing. The combination of optimistic cost estimates with immature technology resulted in cost increases and schedule delays. GAO recommended that DOD, among other things, require officials to document and justify the differences between program cost estimates and independent cost estimates and develop a centralized database of realistic and credible data for cost estimators. GAO also recommended that, to better ensure investment decisions for space programs, estimates could be updated as major events occur within a program that might have a material impact on cost, such as budget reductions, integration problems, and hardware and software quality problems.

GAO, *Space Acquisitions: DOD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems*, GAO-07-96 (Washington, D.C.: Nov. 17, 2006).

TRAs Depend on the Quality and Availability of Credible Data

The quality of a TRA is contingent on the accuracy and relevance of the artifacts, test data, analytical reports, and other information used to support the evaluation. The artifacts, data, and other information collected to evaluate critical technologies may have dependency, functions, and interaction with other program elements that may be outside the evaluation scope or may not be available to the assessment team conducting the TRA. Thus, careful consideration of technology components, systems, or subsystems that may be out of the scope's evaluation should be carefully and selectively considered as part of the TRA design and execution. Further, changes or refinements in requirements, technology designs, or other factors can and often do change that could affect the evaluation. These changes could impact both the information needed to conduct a TRA and the interpretation of previously collected information.

For example, at the earliest stages of development, a technology program may not necessarily have a discreet set of defined requirements and may have more than one potential application or system it is being developed for, so it may be infeasible to assess it for all possible applications. However, information about the system and operational environment that the technology will operate within is necessary to conduct TRAs that will assess the maturity of technologies beyond the lowest levels of the TRL scale.

By regularly documenting data, analyses, and facts, and keeping abreast of changes in requirements, developers and managers are in a better position to facilitate and support TRA efforts. Knowledge, when collected periodically and retained for future reference, can also improve the program management and technology development process.

Chapter 3

Best Practice: A Reliable Process for Conducting Credible TRAs

Credible TRAs follow a disciplined and repeatable process to meet the needs of technology developers, program managers and governance bodies who rely on the information they provide to make important decisions. The TRA is credible when its design and execution considers all the relevant information and executes the key steps in the process, including understanding its purpose, what technologies are being selected and evaluated, how and why critical technologies are being evaluated, and the context of the operational environment in which they will operate. Importantly, all of the people involved in the TRA, from the technology developer or program manager who sponsors the evaluation and provides the evidence to the assessment team to the governance body or program manager who relies on the results for making important decisions, must have a good understanding of the process and how to use the information it provides.

GAO has identified six steps that can produce credible TRA results that technology developers, system integrators, program managers, or governance bodies can use for making important decisions. Best practices within each step should be followed to ensure that comprehensive, high-quality results are produced that can be easily replicated and updated. Table 2 identifies these six steps and links each one to the chapter in this Guide where it and related best practices are discussed.

Table 2: Six Steps for Conducting a Technology Readiness Assessment (TRA)

Steps	Best practices	Associated tasks	Related chapters
Step 1	Design the overall technology maturity assessment strategy for the program or project. Identifies all the technology maturity assessments for the overall program strategy throughout the acquisition, including guidance on reaching agreement with stakeholders on the scope and schedule	• The technology needs of a program are well-understood and the assessment strategy reflects those needs. • The schedule and events needed to conduct assessments was discussed, developed, and documented in one or more strategy documents • The technology maturity assessment strategy is aligned with the systems engineering plan, acquisition strategy, or similar plans.	4
Step 2	Define the individual TRA's purpose, develop, a TRA plan, and assemble the assessment team. Includes developing a plan for a specific assessment of critical technologies and criteria for selecting the team that will conduct the TRA, including agreements such as statements of independence	• A charter, charge memorandum or similar instrument was developed to identify the TRA's purpose, required level of detail, overall scope, TRL definition, and who will receive the TRA report was determined. • The expertise needed to conduct the TRA and specific team members who are independent of the program were determined • The assessment approach was outlined, including appropriate TRL calculators (if used) • An approach for how the data is to be documented and information reported was defined • A plan for handling how dissenting views was identified • Pertinent information needed to conduct the TRA was obtained	4
Step 3	Select critical technologies Includes the criteria and steps to identify and select critical technologies for evaluation; responsible parties facilitating the selection of critical technologies may include the specific organizations, people, and subject matter experts with key knowledge, skills, and experience	• The program's purpose, system, and performance characteristics and system configurations were identified in a technology baseline description document • A work breakdown structure, process flow sheet, or other documents that characterize the overall system, subsystems, and elements were used to select critical technologies • Programmatic and technical questions and the technology's operational environment were used to determine if a technology was critical • Relevant environment for each critical technology was derived from the operational environment	5

Steps	Best practices	Associated tasks	Related chapters
Step 4	Evaluate critical technologies Includes the criteria, analytical methods, steps, people, and guidance used to facilitate the evaluation of critical technologies; the sources and data, analyses, test demonstrations, test environments compared to derived relevant environments, pilots, simulations, and other evidence used to evaluate the maturity and readiness of critical technologies; the agreement of the program manager, technology developer, and TRA lead on what constitutes a specified TRL level, goal, or objective	• TRLs, or another measure were used as a common measure of maturity • Consistent TRL definitions and evidence needed to achieve the designated category or TRL were determined before the assessment • The assessment clearly defined inclusions and exclusions; the assessment team determined whether the test articles and environments were acceptable • The assessment team interviewed testing officials to determine whether the test results were sufficient and acceptable • The assessment team documented all pertinent information related to their analysis	6
Step 5	Prepare, coordinate and submit TRA report Includes the elements to be included in the TRA report and how the report is developed, submitted for initial and final review, and communicated; also includes how dissenting views are addressed, documented, and reported and who is involved	• An official TRA report was prepared that documented actions taken in steps 1-4 above • Official comments on the TRA report were obtained and dissenting views were explained • If the TRA was conducted by the technology developer or program manager for their own internal use where an official report is not required, it should be documented for future reference and use. This may include a TRA self-assessment conducted during early development and later used as a reference source to ascertain initial risks.	7
Step 6	Using TRA results and developing a Technology Maturation Plan Describes how technology developers, program managers, and governance bodies use the TRA results to make informed decisions and how potential risks and concerns are identified and the use of such information in other program risk assessments such as cost and schedule. Includes steps and actions for developing a plan to mature critical technologies that have been assessed as immature; uses the TRA results and other information to establish a road map for maturing technologies to a designated or higher technology readiness level.	• TRA results were used to make decisions about the program's development priorities • Program management identified risks and concerns related to the TRA were provided as inputs to risk, cost, and planning efforts • A technology maturation plan was developed to track progress toward higher technology maturity levels for troubled or selected technologies	8-9

Source: GAO analysis and subject matter expert input | GAO-16-410G.

More Frequent Evaluations of Technology Maturity

Organizations have learned that making more frequent, regular evaluations of the maturity of critical technologies is a best practice. During the early 2000's when DOD and NASA were conducting TRAs, governance bodies used assessment reports at major decision points to determine whether programs that depend on critical technologies were ready to move to the next acquisition phase. Organizations have since expanded the practice and learned that conducting tailored TRAs in periods between decision points as knowledge-building exercises can put program managers and technology developers in a better position to gauge progress, monitor and manage technology maturity, and identify and manage risks before they become more costly.

These six general best practices for organizing and executing TRAs can in some cases be tailored to meet specific goals. For example, goals can range from assisting a technology developer in maturing a prototype to an acceptable maturity to increasing a program manager's knowledge for a better understanding of the transition risks when maturing technologies to demonstrating readiness for integration, test, evaluation, full-scale product development, production, or deployment to providing a governance body with credible information at key decision points. One such example of a tailored approach is through TRAs conducted as project self-assessments, or as peer reviews, against the technology maturation planning. In the case of transition to full-scale product development, a decision maker in an organization would want to ensure that the entire range of best practices is followed to evaluate technology readiness before making a major commitment of resources.

High Quality TRAs

Based on discussions with experts from agencies, commercial industry, non-profits, and academia, high quality TRAs—whether done for technology, system integrators, and program managers or for a governance body—must exhibit the key characteristics described in table 3, in addition to being done periodically. They must be **credible** in both their design and execution, **objective** in their evaluation of credible evidence, **reliable** in the process used to conduct them, and **useful** to technology developers, program managers, and governance bodies.

Table 3: Characteristics of High Quality Technology Readiness Assessments (TRAs)

Key characteristics	Description
Credible	Assessment design, execution, and reporting activity consider understanding the requirements, critical technologies, relevant or operational environment, and integration and interaction with other technologies or dependencies (e.g., timeliness). TRA lead, subject matter experts and practitioners have the relevant experience and knowledge to perform in their designated role

Key characteristics	Description
Objective	Judgments, decisions, and actions surrounding the assessment and TRA report are based on objective, relevant and trustworthy data, analysis, and information; free from internal and external organizational bias or influence
Reliable	Uses disciplined processes that facilitate repeatability, consistency, and regularity
Useful	Technology developers, system integrators, program managers, or governance bodies understand information; it has sufficient detail and is timely and can be acted upon

Source: GAO analysis and subject matter expert input | GAO-16-410G.

The key characteristics are included within each of the best practice chapters, as appropriate. These characteristics are highlighted in **bold** text to link these important principles to key areas, processes, and steps that are vital to ensuring high-quality TRAs. The characteristics are related but not necessarily dependent on one another. For example, a TRA that is not credible or objective in its execution is not likely to be useful to a program manager or governance body when evaluating critical technologies intended for an acquisition program.

In the chapters that follow, the general best practice areas are discussed in detail to help organizations and practitioners understand the processes, concepts, and steps in applying them. Explanations are provided on tailoring the steps to meet specific program goals.

Chapter 4

Best Practice: Including Technology Maturity Assessments in the Program Strategy, Designing the TRA Plan, and Determining the Team

Best practice: The overall program strategy should identify all technology maturity assessments throughout the acquisition, including guidance on reaching agreement with stakeholders about the scope and schedule of the strategy. It also includes development of a plan for a specific assessment of critical technologies and criteria for selecting the team that will conduct the TRA including any agreements such as statements of independence, as needed.

In systems engineering best practices, evaluations of technology maturity are a routine aspect of program management and are evident in the program planning documents that define the program strategy. For example, TRAs and technical assessments are included in the planning documents such as the systems engineering plan, identified in the program's master schedule, and included in the program manager's budget. The TRA is conducted and executed by an assessment team of knowledgeable individuals, often outside of the program office, who have expertise with the technologies to be evaluated and bring objectivity and independence to the activities. The discrete assessments identified in the strategy are accompanied by a detailed plan for the activities. For any particular evaluation, the plan includes defining the purpose and scope of the TRA and identifying the resources, schedule, funding, and personnel needed.

Technical Maturity Assessment Strategy

How technical maturity assessments will contribute to overall program development is discussed with stakeholders and detailed in one or more strategy documents, such as the systems engineering plan or the acquisition strategy. Such documents discuss the purpose and scope of actions to be undertaken for any TRA or other technical assessments that are required for programs preparing for key decision points or stage gates. For completeness and to ensure that technology maturity is **reliable** and is regularly evaluated during development, the documents include placeholders for TRAs called for by the program manager for ensuring that progress towards achieving specified levels of maturity at key decision points for governance is made.[14]

For example, in developing an overall strategy, stakeholders should agree about whether one or more comprehensive TRAs will be required to support one or more key decision points or stage gates. The strategy should also address whether the program will conduct tailored TRAs possibly limited to a single technology or technology group to evaluate the progress in maturing technologies during development. The strategy lays out broad goals and purposes for the TRAs, including when they may be conducted in the acquisition cycle, and how many, at a minimum, will be undertaken. The maturity assessment strategy also might include when tailored TRAs for knowledge building purposes could be conducted to serve as waypoints on progress toward achieving specific program goals for an upcoming decision point.

Another consideration in developing the maturity assessment strategy is to include criteria for initiating the development of mitigation plans to address technology assessed as immature. Organizations may already have similar strategies in place to mitigate risk areas. This Guide puts forth the idea of including a maturation tool in the assessment strategy to identify how immature technologies would be addressed. This tool is called a Technology Maturation Plan (TMP) that lays out the necessary steps for maturing critical technology. While organizations may have similar tools in place, the TMP is encouraged as part of an organizations assessment strategy to address immature or more complex critical technologies. The development of a TMP is further discussed in chapter 9.

The scope of a maturity assessment strategy is program wide and may encompass years of development and multiple TRAs. Every critical technology should be included, perhaps even multiple times, and the strategy will need to allow for flexibility depending on the progress of the development and how quickly the technologies mature. Often the customer

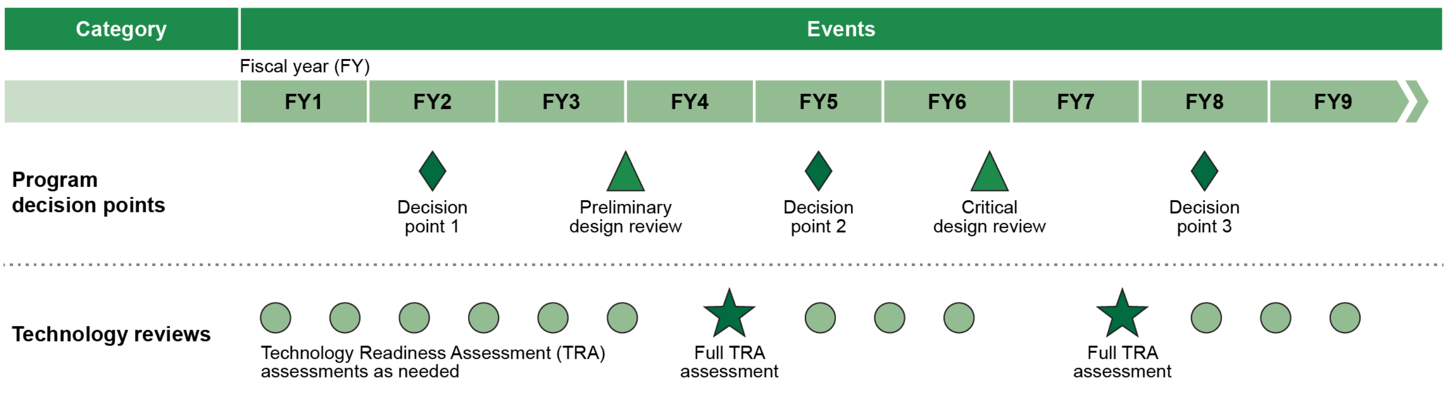
[14]Technical assessments vary in their purpose and scope and how they are identified. TRAs used for governance purposes are prescriptive in their purpose and scope for evaluating the maturity of specific critical technologies at a point in time, whereas technical assessments may be broader in scope and purpose and commonly focus on the larger system, subsystems, and other elements. While TRAs for governance are often conducted by independent teams of subject matter experts, the knowledge-building TRAs are tailored self-assessments for determining the progress of technology maturation.

for a TRA strategy is the governance body or oversight organization of the program. For example, 10 U.S.C. § 2366b(a)(2) requires that a major defense acquisition program may not receive a Milestone B decision until the milestone decision authority certifies that the technology in the program has been demonstrated in a relevant environment on the basis of an independent review. The strategy should allow for sufficient time and resources to complete the assessment before the expected milestone date.

The program's master schedule, budget documents, and test planning documents should contain evidence of the strategic planning for assessing technical maturity. Essentially, the program's master schedule should contain dates for required assessments, including those required for decision points. For example the Department of Energy's policy generally requires that where new critical technologies are being developed, a TRA must be conducted for major system projects and a Technology Maturation Plan prepared, as appropriate, to support the Critical Decision (CD)-2 approval process. Additionally, for situations in which a change in the system design results in a new critical technology element (CTE), post CD-2, an additional TRA may be required prior to CD-3.The master schedule should also indicate where other TRAs associated with knowledge building exercises could be conducted, if needed, even if they are not associated with decision points.

Figure 4 is a notional schedule showing provision for technology maturity assessments. Each program should determine when TRAs for governance and for knowledge building exercises will be conducted, as appropriate. Events will vary by program but will minimally include key acquisition decision points; principal systems engineering and logistics activities such as technical reviews and assessments; planned contracting actions such as request for proposal release, source selection activity, and contract awards; production events and deliveries; and key test activities. TRAs for critical technologies will vary with the number of technologies and their achieved maturity, as demonstrated throughout development. For example, a complex technology entering development at TRL 4 may require more maturity assessments than a less complex technology entering development at TRL 6.

Figure 4: Notional Depiction of the Integrated Schedule for a Program



Source: GAO analysis of agency documents. | GAO-16-410G

Management requirements dictate the timing of required assessments. For example, for DOD's defense acquisition programs a TRA is required before Milestone B. However, the strategy should address the entire developmental period and reflect the resources (labor, materials, and overhead, for example) and consider time or funding constraints for all assessments, whether required to support a decision point or simply to support the need for knowledge.

The Assessment Team

In general, an independent assessment team of subject matter experts from a variety of disciplines is assembled to **reliably** identify or validate the critical technologies, **objectively** evaluate the maturity of those critical technologies, and assign the specific TRLs. Self-assessments based on established TRA best practices are useful as knowledge-building exercises and technical risk mitigation tools. The TRA team, usually recruited by the program manager or other decision authority, is responsible for planning, executing, and documenting the TRA. The team has access to program and contractor personnel, in addition to physical data and should participate in a pre-assessment orientation that includes technical overviews.

The planning documents and the report should provide information on the makeup of this team, including biographies detailing the credentials of each member. In particular, the information should allow someone using the assessment to understand that the team is **objective** and independent of the development program and how the individual members were selected.

The number of individuals appointed to the assessment team depends on the purpose of the assessment, on the requirements imposed by any governance or oversight body, and on the breadth of the subject matter of the technologies. An assessment team of three to five subject matter experts from fields relevant to the technologies to be assessed, all with experience and training in evaluating technology maturity, is recommended. The individuals will study the requirements, review the applicability of the tests and the results of the tests, and prepare the report. For a maturity assessment undertaken for use during a decision point, the governance or oversight body may require that members of the review team to be subject matter experts who are independent of the program to avoid conscious or subconscious bias, or the perception thereof. Much of the value of the process is in the detailed discussion that leads to assignment of a TRL score, and including program team members as observers can be valuable. For other TRAs, such as self-assessments conducted as knowledge-building exercises for program managers or technology developers where the main focus is to mature the technology in their day to day responsibilities, including project team members could be the practical choice. However, **objectivity** in evaluating the evidence is a key requirement that must be observed

It is important to the selection of assessment team members to:

- Ensure that TRA leads, subject matter experts, and practitioners have the relevant experience and knowledge to perform in their designated roles.
- Select enough team members for adequate coverage of technologies. For example if a technology involves operations in space, a team member with appropriate experience in testing such technologies would be needed. The team size will also depend on how many technologies need to be evaluated. For example, if a TRA involves a large number of critical technologies from a number of different technological fields, the team will need more members than if there are only a few critical technologies from related fields. For a successful independent assessment, technical experts must be selected from outside the development program. Typically, an independent assessment team is convened and bases its evaluation on the critical technology primary source documentation provided by the program

manager. Independent assessment team members could be selected from

- laboratories or other research entities independent of the project,
- individuals from federally funded research and development organizations,
- subject matter experts within the agency but not the program, and may include academics, or
- retired personnel.

Once the team is selected, the members should discuss the scope of the project, the resources allocated, and any constraints on funding or schedule and prepare the plan for the particular TRA.

The TRA Plan

TRAs may be intended either to

1. provide a comprehensive evaluation of all the technology elements for decision makers to evaluate as evidence for assessing development progress or

2. evaluate the maturity of a certain critical technology or group of critical technologies to assess progress during development.

The content of the plans may differ between a comprehensive evaluation and an evaluation of a group of critical technologies or a single critical technology. However any TRA plan should contain the necessary information about the purpose of the assessment, the scope of the testing, such as the technologies to be included, expected time for conducting the tests, and a description of how the TRA results will be communicated to stakeholders and others. As the TRA team prepares the assessment plan, a sufficient level of detail for the TRA should be consistent with the level of detail available for the expected level of maturity of the technology at that point in the program. For example, information for technology assessed in the earlier stages of development would not have the same level of detailed information than a technology at a more mature phase of development.

Once the scope of the assessment has been determined, the TRA team should create a detailed schedule that includes key decision points and provides margins for inevitable (but usually unforeseen) delays. It should include a realistic estimate of the resources required considering the number of critical technologies selected for the TRA and a realistic estimate of the duration of the assessment. In particular, the team must assure that the TRA schedule is not overly optimistic or based on estimates constructed to meet a particular finish date. In other words, the time allocated to the assessment should be based on the effort required to complete the activity, the resources available, and resource efficiency. Compressing the schedule to meet a particular date is acceptable as long as additional resources are available to complete the effort that fewer team members would have completed in more time. If additional resources are not available, and the required date cannot be delayed, then the assessment scope will have to be reduced and discussed with stakeholders and documented. A mitigation plan should also be presented to the stakeholders. The essential point is that the team must try to ensure that the schedule realistically reflects the resources that are needed to do the work and should determine whether all required resources will be available when they are needed.[15] If resources may not be available, the team will have to disclose that the compressed schedule curtails the depth of analysis and may jeopardize the maturity of specific technologies under evaluation.

The customers for a TRA plan may include several organizations, such as the governance or oversight body, but the plan may also be created for a more narrow audience—the program manager, systems engineer, technology developer, or independent consultant, to name a few. To begin, the plan must first identify who the customer is and what the needs are for that particular TRA. For example, is the program manager or systems engineer the recipient of the TRA that calculates progress in achieving technical maturity for a specific technology or group of technologies? Or is the TRA to be prepared for a governance body for an upcoming decision point or stage gate for a go/no go decision? In the case of the initial assessment used to begin program development, a broad range of technologies may need to be assessed. In the case of interim assessments, the scope may be more limited. Some questions the plan may address are

- What evaluation criteria will be used to judge the results of a given test?
- How much evidence will be needed to support a given assessment?
- What kinds of evidence will be collected?
- Who will lead the team?
- How will differing opinions on the results of an assessment be handled?
- Will statements of independence be needed?

[15] GAO, *GAO Schedule Assessment Guide*, GAO-12-120G, (Washington, D.C.: May, 2012).

- How should the credentials and experience of team members be documented?
- How much documentation will be needed for each critical technology?
- Who will write the report?
- How will the team communicate with the program?

The scope should also include measures that the team has agreed will describe or quantify the results of the assessment. In addition the team should reach consensus about the tools, such as checklists or automated programs that could be employed.[16] Importantly, the team should agree on the specific objective standards that will be used to determine the sufficiency of evidence. For example, is direct observation of testing by the subject matter experts required, or will written observations of current and past testing be used? How many tests or observations are needed to support a given assessment? How will success be measured? How will disagreements among the experts be documented in the final report? A best practices checklist for TRA team, purpose, scope, and schedule is included below.

Best Practices Checklist: TRA Team and Purpose, Scope, and Schedule for TRA Plan

- The composition of the team is informed by the purpose and scope of the assessment
- The team is the proper size
- The members can maintain objectivity or are independent of the program
- The team includes members experienced in assessing technical maturity and their experience, qualifications, certifications, and training are documented
- The team has developed a master schedule that reflects dates for maturity assessments and decision points along with a written TRA plan
- The team has access to additional subject matter experts from a variety of disciplines
- The TRA's purpose and scope are clearly defined

[16] In some cases, agencies have developed a set of standardized TRL calculators; however, these are guides and at times tailored TRL calculators are more appropriate for a specific application. In these instances, the modified TRL calculators must be reviewed and approved by the TRA team and cognizant project/program management.

- The resources, schedule, funding and personnel needed have been identified
- The level of detail for the TRA is consistent with the level of detail available for the program
- The team has been allotted adequate time and resources to develop the TRA

Chapter 5

Best Practice: Selecting Critical Technologies

Best practice: Selecting critical technologies is fundamental to the TRA process. It includes the criteria and steps used to identify and select critical technologies for evaluation. Responsible parties facilitating the selection of critical technologies may include the specific organizations, people, and subject matter experts with key knowledge, skills, and experience.

Organizations must define what a critical technology is before determining which technologies are, in fact, critical technologies. Today, technologies are more diverse and sophisticated than ever before and can run a wide gamut from defense weapon and satellite systems with embedded software to nuclear waste processing facilities, oil and petroleum systems, or highly distributed IT systems that operate on a national or global scale. DOD developed the most common definition of critical technologies but organizations can adopt or modify them to suit their particular needs. In general, a technology element is considered critical if it is new, novel, and needed for a system to meet its anticipated operational performance requirements or poses major cost, schedule, or performance risk during design or demonstration.

Establishing a disciplined and repeatable process for **reliably** identifying and selecting critical technologies is paramount to conducting a credible TRA. Selecting critical technologies during early technology development and before product development is a best practice and fundamental to conducting a high quality TRA. Subject matter experts with key knowledge, skills and experience are necessary to accurately evaluate elements of the system or architecture design and the operating environments and subsequently identify the enabling critical technologies. It is important to realize that technologies identified as critical may change as programmatic or mission-related changes occur, system requirements are revised, or technologies do not mature as planned.[17]

Critical Technologies Defined

Technology elements are considered critical if they are new, novel, and the system being developed or acquired depends on them to meet its

[17] There are multiple reasons why critical technologies of an acquisition program can change. During technology development, these changes may reflect cost, schedule, and performance trade-offs designed to make a program less risky or more affordable. In other cases, changing or adding critical technologies can increase cost and schedule risk. For example, GAO has found that if performance requirements are added, or changed significantly, to a program later in the acquisition life cycle—such as during product development or final design—these may cause significant cost increases and schedule growth.

performance requirements within defined cost and schedule parameters. Given that a TRL determination is, in most cases, based on demonstrated performance, the critical technology must be defined at a level that is testable as well. Government agencies such as DOD and DOE each use similar definitions.[18] Some agencies also state that technologies may be critical from a manufacturing process or material, measurement, or infrastructure perspective, including whether an organization has a workforce with the necessary skills, knowledge, and experience to fulfill their mission.

Program officials sometimes disregard critical technologies when they have longstanding history, knowledge, or familiarity with them. For example, some organizations will not consider a technology critical if it is has been determined to be mature, has already been fielded, or does not currently pose a risk to the program. This is problematic when these technology elements are being reapplied to a different program or operational environment, particularly when being used in a novel way.

Case study 4 illustrates that officials risk overruns in cost and schedules and can encounter performance shortfalls when they fail to identify all critical technologies for programs with which they have had experience.

[18] DOD Technology Readiness Assessment Guidance, Assistant Secretary of Defense for Research and Engineering (ASD(R&E)), April 2011; U.S. Department of Energy, Technology Readiness Assessment Guide (DOE G 413.3-4A).

Case Study 4: Program Updates Can Change Critical Technologies, from *DOD*, GAO-02-201

The Army began to develop the Crusader—a lighter and more deployable advanced field artillery system to replace the Paladin system—in 1994, and changed its requirements in 2000. In 2002, GAO found that the Army had overestimated the maturity of critical technologies and risked cost overruns, schedule delays, and performance shortfalls by prematurely committing the program to product development. For example, DOD viewed the Army's long time experience with certain technologies within the program as one reason for the Army's failure to identify all critical technologies. GAO recommended, among other things, that the Army further mature the Crusader's technologies before committing to product development and assess the projected capabilities and fielding schedules for future combat systems as part of the Crusader's milestone decision for beginning product development.

GAO, *Defense Acquisitions: Steps to Improve the Crusader Program's Investment Decisions*, GAO-02-201 (Washington, D.C.: Feb. 25, 2002).

All critical technologies must be identified to achieve a comprehensive evaluation of technological risk. It is best to neither under nor overestimate the list of critical technologies. Correctly identifying and selecting critical technologies can prevent wasting valuable resources—funds, capital acquisitions, and schedule—later in the acquisition program. There should be no limitations on the number of critical technologies, but if an overly conservative approach is used and critical technologies are over-identified, resources can be diverted from those technologies that require an intense maturation effort. However, the under-identification of critical technologies because of a real or perceived limitation on the number of critical technologies allowed may prove disastrous in that such areas may fail to meet requirements, resulting in overall system failure.

Challenges in Selecting Critical Technologies

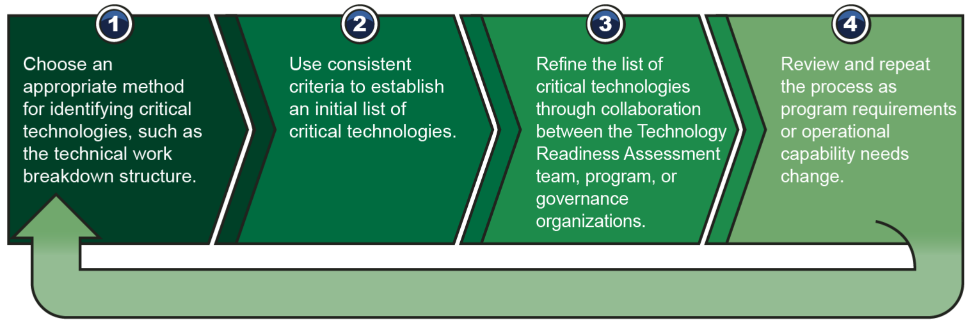
While the process to collect evidence for identifying critical technologies can be a straightforward one, the determination for what constitutes a critical technology is a highly subjective proposition, requiring knowledge, experience, and due professional care.[19] For example, judgements need to be made about what a technology is (e.g., hardware, software, both), what makes a technology critical, and at what level (e.g., subcomponent, component, system, and element) is appropriate to test, demonstrate, and validate key functions of that technology or system. Many critical technologies at the subcomponent or subsystem level may consist of multiple technologies made up of hardware with embedded software. Other organizations such as DOE may define critical technology as the process used to treat waste material. In its May 2005 TRA Deskbook, Appendix D, DOD developed a repository of key questions to help program managers and technology developers identify critical technologies for the various type of applications, such as aircraft; ground vehicles; missiles; ships, submarines, and naval weapons systems; information systems; networked communications systems; business systems; mission planning systems; embedded IT in tactical systems; and manufacturing. Organizations should build similar strategies and tools to help them identify critical technologies.

Steps for Selecting Critical Technologies

Critical technologies should be rigorously and objectively identified and documented to ensure that the evaluation is **objective** and **reliable**, and the information they provide is **useful**. The approach should be open and transparent to everyone in the TRA process. This includes, but is not limited to, representatives from the program office responsible for product development, the test community, and the science and technology, engineering, and user communities. Figure 5 depicts four steps that should help organizations ensure that the process for selecting critical technologies is **reliable**. The steps can be scaled to address programs and projects of all sizes from component technology development to large scale program acquisition.

[19] GAO has found wide variations in the number of critical technologies identified by similar programs. For example, in March 2008, GAO has shown that the Navy's Extended Range Munition Program identified 17 critical technologies, whereas a similar Army program, the Excalibur Precision Guided Extended Range Artillery Projectile, only identified 3 critical technologies. Some, but not all of these differences, can be explained by the differences in the operating environments of the systems, but the subjectivity involved in identifying critical technologies also played a role.

Figure 5: Four Steps for Selecting Critical Technologies



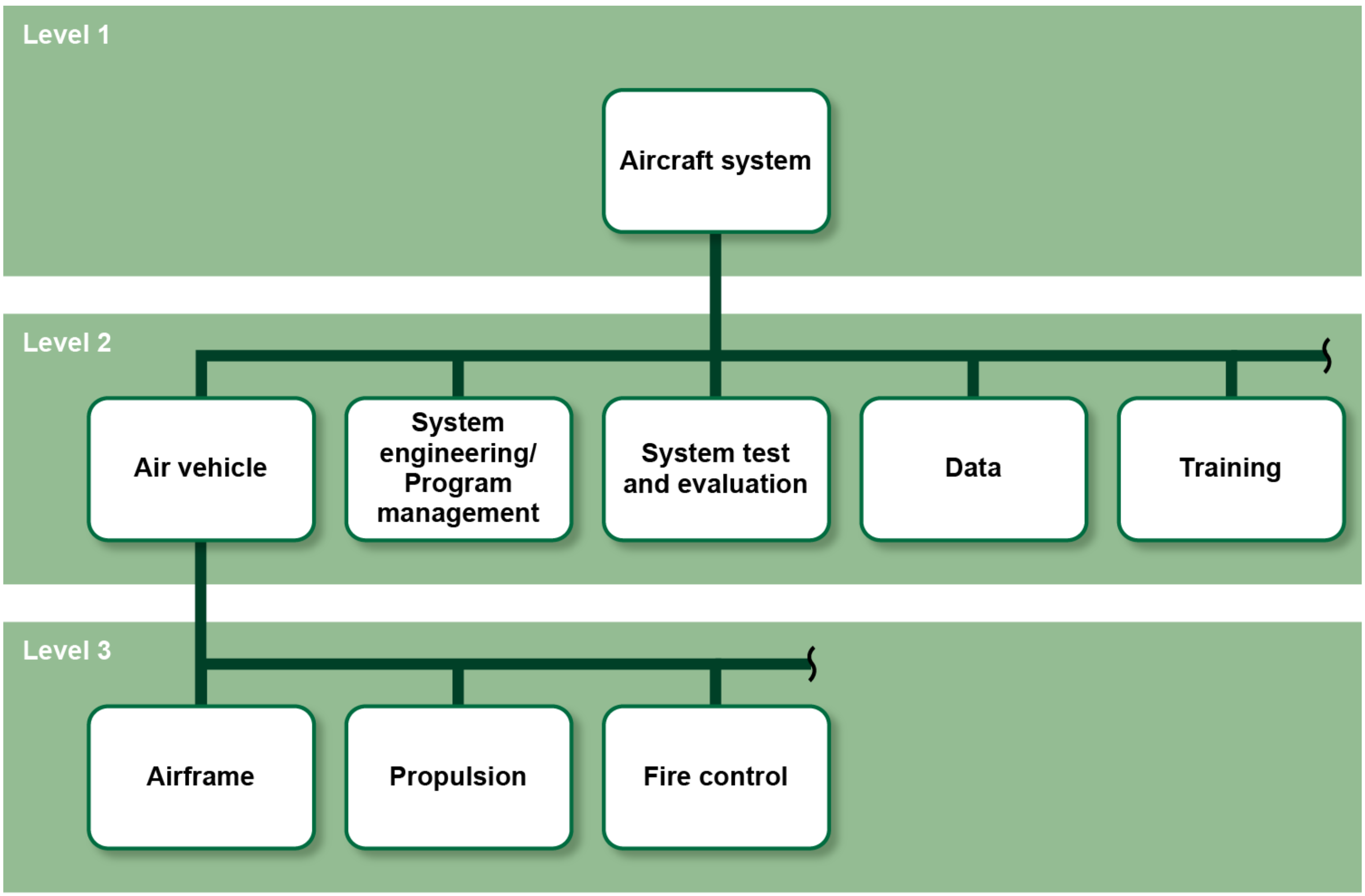
Source: GAO analysis and subject matter expert input. | GAO-16-410G

In Step 1, the assessment team and program manager or an organization policy establish an approach for identifying critical technologies. The most common approach that agencies and other organizations use is the work breakdown structure (WBS)—a product-oriented family tree of tasks relative to hardware, software, services, data, and facilities.[20] The WBS is commonly used because it is a key reference document that looks broadly at all the task sets or elements of a system, subsystem, or software architecture being developed. A technical WBS helps to enforce a rigorous, systematic, and repeatable TRA process when reconciling the identification of critical technologies. It can be used to identify critical technologies as well as low-risk heritage technologies.[21] Figure 6 shows a program WBS with common elements for an aircraft system.

[20]See GAO, *Cost Estimating and Assessment Guide* (GAO-09-3SP). ch. 8, for examples of standard work breakdown structures for, among others, surface, sea, and air transportation systems; military systems; communications systems; and systems for construction and utilities.

[21]Heritage technologies can become critical if they are being used in a different form, fit, or function.

Figure 6: Common Elements of a Work Breakdown Structure

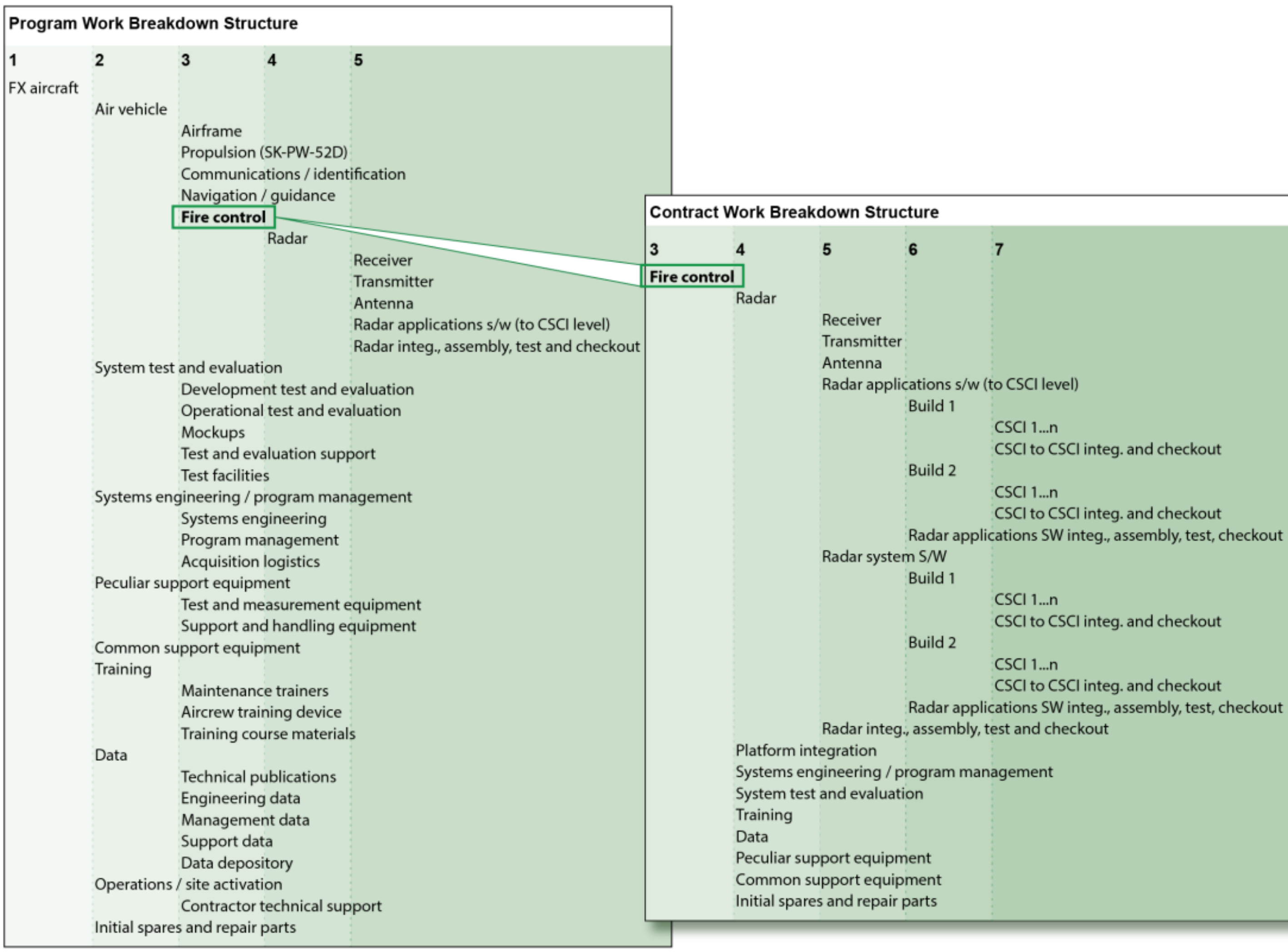


Source: © 2005 MCR, LLC, "Developing a Work Breakdown Structure." | GAO-16-410G

A well-developed WBS or equivalent source of information is essential to the success of all acquisition programs. The WBS is typically developed and maintained by a systems engineering process or business function that produces a product-oriented family tree of elements, or tasks that are critical to the successful development of the project. It can be thought of as an illustration of the work that will satisfy a program's requirements. These elements such as hardware, software, and data are broken down into specific lower level elements. The number of levels for the WBS varies from program to program and depends on a program's complexity and risk.

It is important that the WBS comprehensively represents the entire program at a level of detail sufficient to manage the associated size, complexity, and risk. At the lower levels, a contractor or technology developer must also develop a WBS that extends to include the lower-level components to reflect its responsibilities. Because it is composed of all products that constitute a system these lower-level WBSs are an appropriate means to identify all the technologies used by the system. Depending on the new or novel technologies that are needed for a system, critical technologies may be selected from these lower level components. Figure 7 shows how a contract WBS may be depicted from the larger WBS to illustrate one aspect of lower level components.

Figure 7: A Contract Work Breakdown Structure



Source: Department of Defense. | GAO-16-410G

A WBS for a project that has software elements should be broken down into specific lower level components as needed. Table 4 shows a WBS for a software project.

Table 4: Software Implementation Project Work Breakdown Structure

Level 2 element	Level 3 element
1.1 Project management	
1.2 Product requirements	1.2.1 Software requirements 1.2.2 User documentation 1.2.3 Training program materials 1.2.4 Hardware 1.2.5 Implementation and future support
1.3 Detail software design	1.3.1 Initial software design 1.3.2 Final software design 1.3.3 Software design approval
1.4 System construction	1.4.1 Configured software 1.4.2 Customized user documentation 1.4.3 Customized training program materials 1.4.4 Installed hardware 1.4.5 Implementation & future support
1.5 Test	1.5.1 System test plan 1.5.2 System test cases 1.5.3 System test results 1.5.4 Acceptance test plan 1.5.5 Acceptance test cases 1.5.6 Acceptance test results 1.5.7 Approved user documentation
1.6 Go live	
1.7 Support	1.7.1 Training 1.7.2 End user support 1.7.3 Product support

Source: Project Management Institute Inc., Practice Standards for Work Breakdown Structures, Second Edition, 2006. | GAO-16-410G

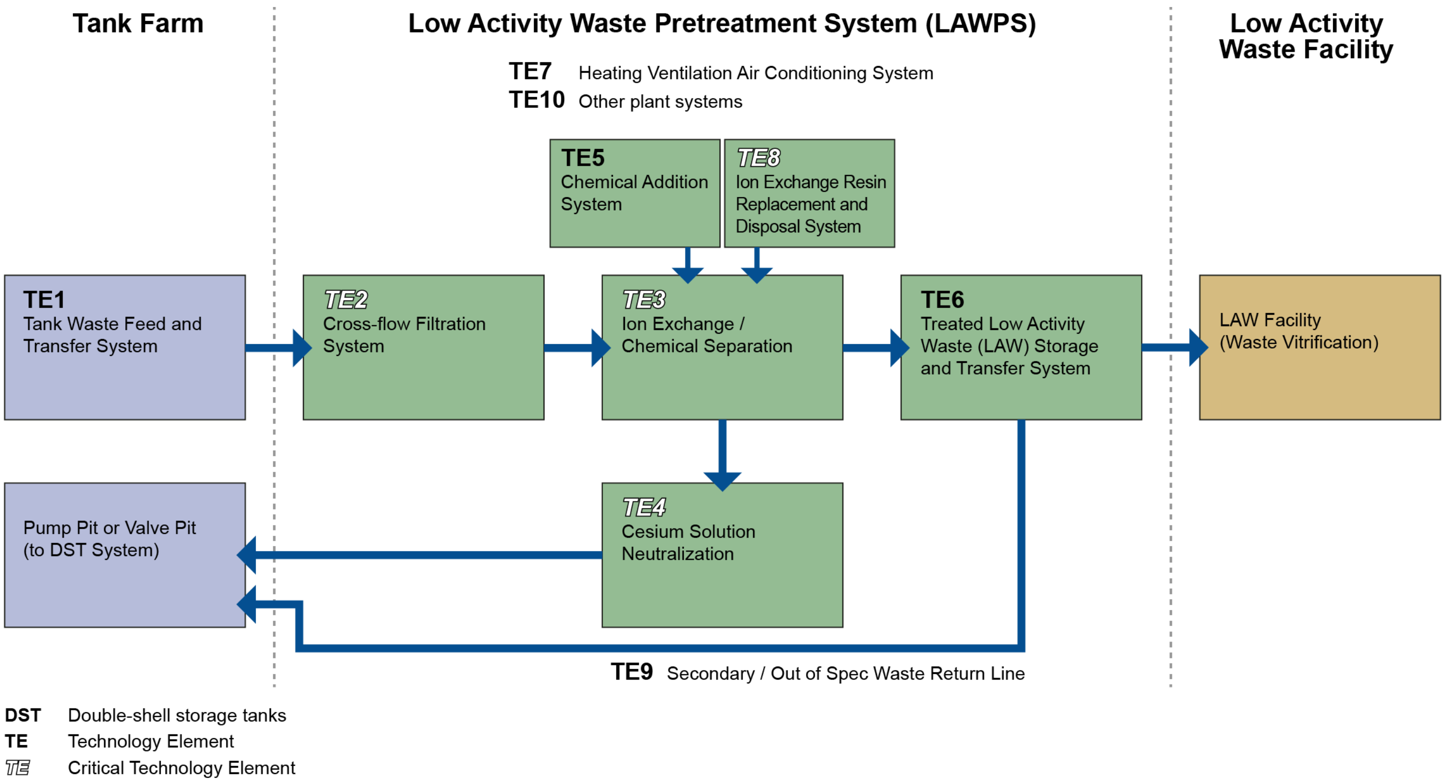
The WBS has several beneficial attributes, including that it

- is readily available;
- evolves with the system concept and design;
- is composed of all products that constitute a system and, thus, is an apt means to identify all the technologies used by the system;
- relates the system design and architecture and, the environment in which the system is intended to be employed; and
- reflects the system design and architecture and the environment and performance envelope for each product in the system.

The WBS or similar approach should be possible for most programs, because it can be viewed most simply as a structure around which to organize a program, no matter its size. At the earlier phases of development, a detailed WBS may not be available. It is acceptable to substitute early requirements and environments from capability documents, broad agency announcements, requests for information, market surveys, actual results from government- or industry-funded efforts, program risk registers, and any initial system design concepts being considered. Programs during this phase may also use a reverse engineering approach that relies on program requirements to determine which technologies are critical by focusing on those needed for the system to meet its performance requirements.

There are instances when use of a WBS is not possible due to the early phase of development of a program, or due to the nature of the project, WBS-based technology maturation planning is not necessarily appropriate. For example, DOE's Office of Environmental Management has determined that the WBS may not be all-inclusive for identifying critical technologies for their application, so they examine system flow sheets or diagrams (for example, those of chemical or nuclear waste processing facilities) to help identify critical technologies. In this approach, DOE determines the technologies by examining those technology elements that constitute the system flow sheet. This includes examining the interfaces and dependencies with other facilities and supporting infrastructure. All the technologies are evaluated against criteria to determine which ones are critical technologies. Figure 8 is a simplified flow sheet that shows the technology elements for the Low Activity Waste Pretreatment System project at DOE's Hanford site.

Figure 8: A Process Technology Flow Diagram (simplified)



Source: GAO, adapted from Department of Energy Office of River Protection. | GAO-16-410G

In step 2 of figure 5, criteria in the form of questions can be used for determining the initial list of critical technologies. The program manager or technology developer (or a designee) is generally responsible for identifying the initial list of critical technologies using these questions coupled with the WBS, process flow diagram, or a similar approach. Ideally, this early identification of critical technologies will allow the program or technology manager to identify any additional areas of technical expertise that are needed on the TRA team in order to fully evaluate the program. However, during the actual assessment, the TRA team is responsible for either validating the proposed critical technologies or determining them as part of the independent process.

We have compiled a list of questions from government agency TRA guides that can be used as baseline in defining critical technologies and assisting towards reconciling any disagreements between the team members, programmatic teams, or governance bodies. If the answer is “yes” to both sets of questions listed below, then the technology should be considered for the initial list of critical technologies.

- Programmatic questions
  - Do requirements definitions for this technology contain uncertainties?
  - Does the technology directly affect a functional requirement?
  - Could limitations in understanding this technology significantly affect cost (for example, overruns) or affordability?
  - Could limitations in understanding this technology significantly affect schedule (for example, not ready for insertion when required)?
  - Could limitations in understanding this technology significantly affect performance?
- Technical questions
  - Is this technology new (for example, next generation)?
  - Is the technology used in a novel way?
  - Has the technology been modified?
  - Is the technology expected to perform beyond its original design intention or demonstrated capability?
  - Is the technology being used in a particular or different system architecture or operational environment than it was originally intended or designed for?[22]
  - Could the technology have the potential for adverse interactions with systems with which the technology being developed must interface?

These questions are not comprehensive; they serve as a starting point for in-depth questions that could be answered at different organizational levels. More detailed questions can be built from the organization’s knowledge base using engineering judgment or lessons learned and could be refined or tailored to match the program requirements. Subject matter experts inside

[22] The readiness of technology can vary greatly depending on the intended environment in which the system will operate. When there are deviations from the prior environment and the intended environment, the planned use of the technology by the program or project needs to be re-evaluated (i.e., a mature technology in one environment may be less mature in another).

or outside the program with the requisite technical knowledge and the independence needed to make unbiased, **objective** decisions should guide answering the questions asked for each critical technology candidate. In the July 2009 TRA Deskbook, DOD provided questions for identifying critical technologies for a variety of acquisition programs, including aircraft; ground vehicles; missiles; ships, submarines, and naval weapons systems; information systems; networked communications and data management systems; business systems; mission planning systems; and information technology embedded in tactical systems.[23]

A best practice is to annotate the WBS, or a logical alternative such as a program risk register, and then list critical technologies with the reasons why other technologies were not selected. This allows anyone who participates in the TRA to see an account of how the critical technologies were systematically determined rather than through an undocumented or arbitrary selection process.

In step 3 of figure 5, the TRA team either validates or refines the initial list of critical technologies. The TRA team resolves any internal disagreements over critical technology determinations and documents the reasons behind each determination. If consensus cannot be reached, the TRA team leader makes the final determination, but alternate viewpoints should be included in the final report.

In addition, an independent review team may critique the critical technology list or make its own list. If the TRA is being conducted for governance purposes, the list of critical technologies may be reviewed by members of the governance body, including acquisition executives, component heads, and agency senior leaders. Critical technologies may be added to the list or removed, but these decisions must be documented and should be transparent. If the TRA is being conducted for program management or knowledge-building purposes then this process can be less formal but should still be followed to the maximum extent possible.

A best practice for organizations is to develop or tailor guidance on how best to approach the determination (identification and selection) of critical technologies for their specific application, including communication across

[23]The 2009 TRA Deskbook is no longer in use and was replaced by DOD's 2011 Technology Readiness Assessment Guidance. GAO refers to the 2009 TRA Deskbook because it contains useful examples that could be used by practitioners and experts.

the organization with regard to decisions or activities that could affect how critical technologies are identified. The most common pitfall among organizations is that changes are not communicated to others. This often happens when technology development and product or system development occur in parallel under different organizations.

A best practice for the TRA team in identifying critical technologies is to consider their intended operational environment, and their interaction with systems with which the technology being developed must interface. This is because technologies can be disregarded as critical when programs have longstanding history, knowledge, or familiarity with them. By understanding the operational environment and their interaction with other systems, critical technologies can be more easily identifiable because it highlights whether it is being used in a new or novel way and whether it can have an adverse impact on the system.

In step 4 of figure 5, the program manager, TRA team, or governance body repeats the determination process, as needed. During technology and product development, it is likely that decisions will be made that could affect the list of critical technologies. These decisions may include changes to the system's proposed capabilities, its design, or its intended environment. In addition, alternative technologies may be selected as new technologies become available or if technologies do not mature as expected. Thus, critical technologies may be added or removed from the list during the TRA process. These decisions should be documented and reviewed. Therefore, an early agreement should be reached on how changes to the list of critical technologies will be handled, so that those involved in the TRA process can be aware of changes in other organizations, departments, or centers that could affect the assessment and that communication links be established between technology developers and system developers.

Identifying Other Important Technologies and Programmatic Issues

While selecting critical technologies is fundamental to the TRA, some technologies may not rise to the level of a critical technology but could potentially pose concern if certain conditions changed. For example, the assessment team may identify additional "watch items" that represent significant risk areas. Highlighting these watch items adds an additional level of visibility throughout the acquisition life-cycle.

In addition, while TRAs are not generally considered to be program assessments because the focus is on individual technologies, organizations have included areas beyond critical technologies as part of their internal TRA guides and processes. For example, the Air Force and DOE consider programmatic issues important to evaluations because these can affect technology development. These organizations include program issues in their TRL calculators, which are tools for identifying, evaluating, and tracking critical technologies.[24]

Best Practice Checklist: Selecting Critical Technologies

- A rigorous, **objective**, **reliable**, and documented approach, based on the WBS or other key program documents was used to initially identify critical technology candidates.
- The intended operational environment was considered, including potential adverse interactions with systems which the technology being developed must interface.
- Critical technologies were selected during early development and each critical technology's maturity level was evaluated in the program's operational environments.
- A relevant environment was derived for each critical technology from those aspects of the operational environment that is determined to be a risk for the successful operation of that technology.
- Critical technologies were initially selected following a **reliable** process that is disciplined and repeatable with defined criteria, such as the questions in this chapter, and then confirmed, using increasingly platform- or program-specific questions and requirements.

[24]There are mixed views on the use of TRA calculators in the expert community. Some experts believed that calculators simplify the process for determining the appropriate TRL for a given technology. By presenting a standard set of questions to users, calculators also make the TRA process repeatable. The standard format facilitates the comparison of different technologies and can accommodate both hardware and software development programs. Other experts do not agree with the use of calculators because of concerns associated with box-checking where critical evaluation could be compromised.

DOE is one organization that has developed standard TRL calculators to address not only technical maturity, but also programmatic and manufacturability aspects, associated with the critical technology elements. Additionally, due to the general types of application of the TRA process within the DOE Office of Environmental Management (i.e., radioactive chemical waste processing systems), that organization includes TRL calculators that assess the maturity of the integrated processing system at critical decision points in the project.

- Critical technologies were defined at a level that is testable, which could include the software needed to demonstrate their functionality.
- The assessment team documented the reasons why technologies were selected as critical, including reasons why other technologies were not selected.
- The number of critical technologies chosen for assessment was not arbitrary but was based on solid analysis using the WBS, process flows, or other technical documentation.
- When significant program changes occurred, critical technologies were reassessed possibly causing some to be added or removed from the list of critical technologies.
- Subject matter experts with appropriate and diverse knowledge selected and reviewed the critical technologies.

Chapter 6

Best Practice: Evaluating Critical Technologies

Best practice: Evaluating critical technologies requires disciplined and repeatable steps and criteria to perform the assessment and make credible judgments about their maturity. The evaluation of each critical technology must be based on evidence such as data and test results. It is critical that the program manager, technology developer, and assessment team agree on what constitutes a specified TRL, goal, or objective for the results to be considered valid.

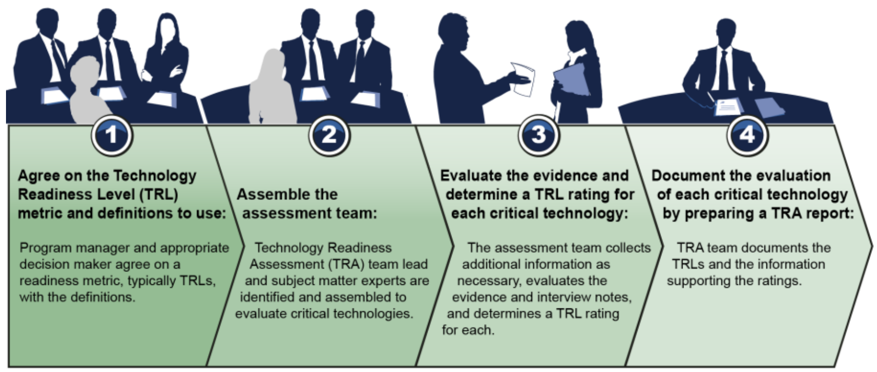
Effectively evaluating critical technologies is essential to the success of acquisition programs that integrate them. The goal of the evaluation is to assign a TRL for each critical technology which is determined through an **objective** evaluation of information against general criteria as defined in the TRL standards and more specific criteria set forth by the program manager, technology developer, and assessment lead.

To determine the maturity and readiness of critical technologies, the assessment team must rely on pertinent information to conduct a credible evaluation of critical technologies. Such information may include test plans and results, analytical reports, schematics and design drawings, and other key information. Depending on whether the evaluation is to certify the readiness of critical technologies for a governance body at a decision point or is a knowledge-building exercise to monitor the maturity of technologies, both the program manager and the assessment lead should understand what the TRA is being conducted for, what constitutes sufficient evidence that a specified maturity level for each critical technology has been achieved, and the operational environment the technology is expected to operate within.

Steps for Evaluating Critical Technologies

Evaluating critical technologies is fundamental to a TRA. Figure 9 depicts four steps that can help organizations ensure that an evaluation is **objective** and **reliable** by applying a disciplined and repeatable process. These steps can be tailored to accommodate organizational structures, processes, and policies.

Figure 9: Four Steps to Evaluate Critical Technologies



Source: GAO analysis and subject matter expert input. | GAO-16-410G

In step 1, the program manager, taking into account organizational policies and practices, determines the measure for maturity, including the definitions to be used. It serves as a common language between the assessment team, program staff, program manager, technology developer, and governance bodies. The most widespread and accepted measure is TRLs. TRL definitions describe the recommended effort and evidence needed to show the maturity of a technology. Congress has required that specific TRLs be achieved for certain DOD programs before they can proceed with system development and GAO has used them in program audits.[25] TRLs are chosen from an ordinal 1-9 scale as discussed in chapter 1, figure 1. Organizations may adopt the TRL definitions provided in this Guide or modify them to accommodate their specific technologies, application, or other characteristics. Additionally, early agreement among process stakeholders for what constitutes both the system and component, as well as what defines relevant or operational environment, is essential for meaningful and credible demonstrations in support of a TRL determination.

In step 2, the program manager or their designee selects the assessment team lead and team members that have the relevant knowledge,

[25] 10 U.S.C. § 2366b requires, in part, that the Milestone Decision Authority (MDA) certify that the technology used in major defense acquisition programs, has been demonstrated in a relevant environment before Milestone B approval. The Under Secretary of Defense for Acquisition, Technology, and Logistics relies on assessments by DOD's Assistant Secretary for research and engineering in consultation with the Deputy Assistant Secretary for developmental test and evaluation to support this certification.

experience, and expertise to evaluate the critical technologies. The assessment team may change as the critical technologies and program evolve throughout their development. For example, as technologies become more mature, systems engineers and others who have a broader understanding of the program technologies and their integration may be as important as the subject matter experts were earlier in the program.

The assessment team must be **objective**. At some organizations or within certain types of industries, it may be difficult to assemble an assessment team that is independent when conducting TRAs for a decision point, when independence is vitally important. This may be because of a limited availability of subject matter experts, cost considerations, or other factors. It may be necessary to establish a review board that can **objectively** and independently review the assessment team's approach, the findings and conclusions reached, or any disagreements among parties about the conclusions. The review board can serve as the independent governance body in the TRA process to ensure that the evaluation is **objective** and **credible**. For example, if the independent review board does not agree with the TRA report's findings or if agreement cannot be reached between the program manager and the assessment team, the disagreement can be documented and, along with the evidence on both sides of the disagreement, and presented to the governance body.

Organizations may or may not require an independent assessment team or review board, but the inclusion of an independent assessment team is considered a best practice. In general, the level of independence and resources allocated to this process depend on the type of TRA and investment in the program. TRAs associated with decision points (that is, governance) generally require a high degree of independence and rigor to provide decision makers with fact-based information about the readiness of the critical technologies. Program managers and technology developers conducting TRAs to inform maturation efforts may chose approaches that require more limited resources, such as checklists, TRL calculators, and subject matter experts internal to the program.

In step 3, the assessment team reviews the information and, if necessary, obtains additional information from the program manager and technology developer in order to evaluate critical technologies and assign TRL ratings. The assessment team should consider, when available and relevant to the system being evaluated, any analogous system technology readiness assessments. Additionally, given cases where synergy can be gained through similar systems, consistent relevant/operational environments, related concept of operations, and the technology is accessible to leverage (for example, product, intellectual knowledge, and pertinent historical reference), the assessment team should take full advantage of applicable technology maturity artifacts. Information to review can include, but is not limited to, a summary of the program's purpose, requirements, key performance parameters, and capabilities so that the assessment team can **objectively** evaluate the critical technologies in proper context. The TRA team considers the information and reaches a consensus within the team, with the following options

1. The assessment team reaches agreement because the fidelity of the test article (or digital model or constructive simulation) and test or simulation environment are appropriate, data are sufficient and the results are acceptable such that no further evidence or evaluation is needed.[26]

2. If the assessment team determines that information is insufficient to render a credible decision, the TRA team asks the program manager for more information to make a TRL determination for each critical technology. The interaction between the assessment team and program manager is often an iterative process as discussions can highlight the need for more information, or pose additional questions.

3. The assessment team may determine that TRL level is not established because the fidelity of the test article or test environment is insufficient and, therefore, information and test results are inconclusive. Such cases are unusual but can occur. When they do, the TRA team identifies the inadequacies and works with the program manager to determine what must be done to obtain an appropriate test article or to achieve an appropriate test environment to ensure the critical technology has been

[26] The assessment team defines the appropriate (or acceptable) test environments, which may differ from those the program manager chose. The test environment should reflect what was determined to be the appropriate relevant environment for the technology being tested. Sufficiency of data could be a statistical issue—as for systems with requirements such as probability of *x*—to meet requirements. It is the lower error bar that must be greater than or equal to the required level. Engineering judgment plays an important role in determining what is acceptable. For example, an overdesigned system (assumed to be more costly) will demonstrate acceptability with minimal data, while a marginal system will require a lot of data (assumed to be costly) to tighten-up the statistics. Engineering judgment could allow a "Goldilocks" system—that is, acceptable performance (system not too expensive) requiring not too much data (not too expensive) to prove acceptability.

adequately tested in a relevant or operational environment to render a TRL number assignment.

A best practice is to develop guidance on communication across an organization with regard to decisions or activities that could affect how critical technologies are identified. The most common pitfall among organizations is that changes are not communicated to others, particularly when technology development or system development occurs in parallel under different organizations. Such miscommunications can be costly and result in unnecessary schedule delays because certain decisions could change which technology elements are critical.

In step 4, the TRA team records the TRL rating of each critical technology with a summary, including supporting documentation, of the justification for the assigned TRL. Table 5 provides examples of the types of supporting information that would be required to support each TRL.

Table 5: Technology Readiness Levels (TRLs) Supporting Information for Hardware and Software

		Supporting information	
TRL	**Definition**	**Hardware**	**Software**
1	Basic principles observed and reported	Published research that identifies the principles that underlie this technology; references who, where, and when	Basic research activities, research articles, peer-reviewed white papers, point papers, and early laboratory model of basic concept may be useful for substantiating the TRL
2	Technology concept or application formulated	Publications or other references that outline the application being considered and provide analysis to support the concept	Applied research activities, analytic studies, small code units, and papers comparing competing technologies
3	Analytical and experimental critical function or characteristic proof of concept	Results of laboratory tests performed to measure parameters of interest and compared to analytical predictions for critical subsystems; references who, where, and when these tests and comparisons were performed	Algorithms running on a surrogate processor in a laboratory environment, instrumented components operating in a laboratory environment, or laboratory results showing validation of critical properties
4	Component or breadboard validation in a laboratory environment	System concepts have been considered and results from testing laboratory scale breadboards; references who did this work and when; provides an estimate of how breadboard hardware and test results differ from the expected system goals	Advanced technology development, stand-alone prototype solving a synthetic full-scale problem, or standalone prototype processing fully representative data sets

		Supporting information	
5	Component or breadboard validation in relevant environment	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment; addresses how the "relevant environment" differs from the expected operational environment, how the test results compare with expectations, what problems, if any, were encountered, and whether the breadboard system was refined to more nearly match the expected system goals	System architecture diagram around technology element with critical performance requirements are defined; includes a processor selection analysis and a simulation/stimulation (Sim/Stim) laboratory buildup plan. Software is placed under configuration management and identifies commercial-of-the-shelf/government-off-the-shelf components in the system software architecture
6	System and subsystem model or prototype demonstration in a relevant environment	Results from laboratory testing of a prototype system that is near the desired configuration in performance, weight, and volume; answers how the test environment differs from the operational environment, who performed the tests, how the test results compared with expectations, what problems, if any, were encountered, and what problems, plans, options, or actions need to be resolved before moving to the next level	Results from laboratory testing of a prototype package that is near the desired configuration in performance, including physical, logical, data, and security interfaces; comparisons of tested environment and operational environment are analytically understood; analysis and test measurements have been obtained by quantifying contribution to systemwide requirements such as throughput, scalability, and reliability; analysis of human-computer (user environment) has begun
7	System prototype demonstration in an operational environment	Results from testing a prototype system in an operational environment; answers who performed the tests, how tests compared with expectations, any problems encountered, the plans, options, or actions to resolve problems before moving to the next level	Critical technological properties have been measured against requirements in an operational environment
8	Actual system is completed and qualified by test and demonstration	Shows testing results of the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate; the system's ability to meet its operational requirements has been assessed and problems documented; plans, options, or actions to resolve problems have been determined before the final design	Published documentation and product technology refresh build schedule exist for the system; software resource reserves have been measured and tracked
9	Actual system has been proven in successful mission operations	Operational, test, and evaluation reports	Production configuration management reports confirm operational success; technology is integrated into a reuse "wizard"

Source: Department of Defense. | GAO-16-410G

The program manager and technology assessment team use this supporting information when writing the TRA report. If the TRA team and program manager cannot reach consensus on a TRL, this must be presented in the TRA report and accompanied by evidence that supports both sides (see chapter 7 for how dissenting views are prepared and documented).

Relevant Information Must Be Used to Evaluate Critical Technologies

Credible TRAs evaluate and rely upon artifacts and information such as requirement documents, analyses, test reports, and environmental test considerations. The availability of such information can depend on the acquisition phase, technology application, and level of complexity. These can range from simple technologies with just a few drawings to analytical reports on nuclear waste facilities, space systems, defense weapon systems, or globally distributed information technology business systems. It is important that organizations collect the necessary information so the assessment team can make a credible determination of the TRL from the supporting documentation. Table 5 lists the typical generic documentation that should be extracted or referenced to support a TRA assignment. Because not all are inclusive and because they can vary by technology and application, organizations should tailor these definitions to accommodate their own technology application.

Operational Environment Is Key to Evaluating Critical Technologies

As technologies mature, periodic TRAs are conducted to determine whether the supporting information can show the state of progress and whether it has reached a certain TRL goal or expectation. The context is that critical technology performance must ultimately be demonstrated in a relevant environment before it is considered mature enough to begin integration into the larger acquisition program, typically at TRL 6-7. At TRL 7, critical technology performance must be demonstrated in an operational environment that addresses all the operational requirements and specifications required of the final system. As a result, practitioners and assessment team must thoroughly understand the broader system requirements, design, and architecture.

For critical technologies related to information technology, the environment includes physical, logical, data, and security environments

- a logical environment includes other applications, run-time (operating system, middleware), security interfaces, and web enablement
- data environment includes formats, data rates, latency
- the security environment includes firewalls, appliqués, methods and describes the nature of attacks

The assessment team conducting the TRA documents the state of the critical technology (experimental test article, breadboard, brass board, or prototype) and how its TRL rating differed from the expected maturity goal, if at all. The description of the test article includes drawings and photographs; the assessment team may have examined the article to verify that these are acceptable artifacts. The test environment must be described in sufficient detail that the assessment team can understand how the test environment differs from the operational environment. Test results include demonstration of performance and sufficiency. Adequate performance is demonstrated when test results show that the test article performed as required. Sufficiency is demonstrated when enough repetitions with consistent results have demonstrated required statistical significance. A minimum number of repetitions is required to achieve statistical significance. In addition, testing and performance verification may be augmented with modeling and simulation. However, when the results are statistical in nature (such as probability of detection) many repetitions may be required to demonstrate the required statistical significance.

When and where applicable, other supporting information includes

- Identification of the test agency
- When and where tests were performed
- Cause of problems encountered, their solutions, and resulting changes in the test plan
- Unresolved issues discovered in testing and the plans, options, or actions required before moving further in development

Creating Critical Technology Subsets for Exceptionally Large or Complex Programs

Critical technologies need to be selected and named for the technologies themselves, not the functionality or other nontechnology approaches. Since a TRL rating reflects the technology being evaluated, the focus should remain on that selection. As mentioned in chapter 5, identifying critical technology is challenging. Critical technologies can be subcomponents, components, subsystems, or systems composed of hardware, software, or both. One of the best practices for making those selections is that the technology must be defined at a level that is testable. For programs with an unwieldy number of critical technologies, especially major acquisition programs that are systems of systems, programs may find it beneficial to group those critical technologies into several smaller, logical subsets that are easier to track, allowing for a more focused evaluation. For example, while a program may have a hundred critical technologies, similar critical technologies could be grouped into 6-8 subsets of 10-12 critical technologies. Specifically, the F-35 program office (formerly called Joint

Strike Fighter) identified critical technology areas encompassing avionics, flight systems, manufacturing and producibility, propulsion, supportability, and weapons delivery system that were made up of many components. However, as mentioned above, no matter how those critical technology areas are defined they must be testable or made up of testable elements. In addition, it is important to note that the TRL is determined by the lowest TRL of critical technologies within a group, and is not an average of all the TRLs in a subset or larger group set.

Best Practice Checklist: Evaluating Critical Technologies

- TRLs, or another agreed upon measure, were used as a common language between the TRA team, program manager, and governance body.
- The assessment team verified that the test article and the relevant or operational environment used for testing were acceptable and validated that the results were sufficient.
- **Credible** and verified information were used as evidence for the assigned TRL such as requirement documents, analyses, test reports, and environmental test considerations.
- **Objective** independent review teams conducted the TRL assessment, particularly for decision point or stage gate reviews by governance bodies.
- The TRL rating of each critical technology was documented including a summary, supporting documentation, and justification for the assigned TRL.
- Technologies should be at TRL 6 or 7 before integration into larger acquisition programs.

Chapter 7

Best Practice: Preparing the TRA Report

Best practice: This practice includes elements in a TRA report and how the report is put together, submitted for initial and final review, and communicated. This practice also includes how dissenting views are addressed, documented, and reported, and who is involved in the process

TRA reports provide technology developers, program managers, and governance bodies with **credible**, **objective** and **useful** information about the maturity of technology, its state of development, and potential areas of risk. Preparing TRA reports includes essential reporting elements, disciplined processes to create them, and predefined approaches to communicate assessment results. TRA reports are important inputs for decision makers and governance bodies as they consider whether programs are ready to proceed to the next stage of development, production, or construction. They can also highlight key knowledge gaps, potential concerns, and risks that might need to be addressed by providing more time and money, reducing performance requirements, or utilizing alternative technology. TRA reports generated from knowledge-building exercises might have a narrower scope or fewer external reviews than those that support key decisions, but, if done well, they provide useful documentation of the status of key technologies and the progress made in maturing them and inform the path forward on how to mitigate potential technology risks. Finally, for auditors, the TRA report provides sufficient evidence of the practices used to conduct trustworthy TRAs. Because stakeholders review TRA reports with different perspectives and goals, information must be presented clearly, logically, and usefully.

The TRA Report

TRA reports are prepared to certify the readiness of critical technologies at key decision points or as knowledge-building exercises that document the maturity of technologies during the interim periods between decision points. When reports are prepared to certify the readiness of critical technologies at a decision point, governing authorities use them to determine whether a program that depends on them is ready to move to the next acquisition phase. This chapter describes the process and steps for preparing a TRA report that will be used at a decision point because it embodies all the best practices for preparing a **credible** report that is both **objective** and **useful**. When the report is prepared as part of a knowledge-building exercise, organizations may tailor the processes as necessary because these do not involve governance bodies where independence and strict levels of review are a requirement and where greater cost may be incurred to conduct them.

In addition, whereas TRA reports prepared for governance bodies are developed to certify whether critical technologies have met an expected TRL rating at a decision point, TRA reports prepared as part of knowledge-building exercises for program managers and technology developers are conducted with a focus on the progress made in maturing technologies. Therefore, the information collected and generated from such exercises is to be used as an internal source of information for managing such efforts. For example, TRA reports for maturing technologies can be used to (1) learn about specific aspects of technology development (that is, identify gaps in maturity or areas that may be challenging), (2) gather evidence to continue development efforts or initiate steps toward using an alternative or backup technology, or (3) determine whether critical technologies are ready for a TRA for governance bodies at an upcoming decision point.

Figure 10 shows an example TRA report template that identifies the types of information that should be included. Each organization should tailor the template to accommodate the way it will use the report. For example, some organizations prepare briefing charts as a TRA report to follow their internal practices. Others prepare detailed reports with specific formatting requirements. At a minimum, organizations should ensure that the suggested reporting elements are included.

Figure 10: Technology Readiness Assessment Report Template

EXECUTIVE SUMMARY

Briefly state who requested the Technology Readiness Assessment (TRA), what organization was responsible for conducting the TRA, what technology was assessed. Provide a summary table of the critical technologies and corresponding Technology Readiness Levels (TRL) determined during the review.

INTRODUCTION

Background

Provide project/program overview and background information (i.e., general description of the program and the technology system, including the critical technologies to be assessed).

Purpose and Scope of the TRA

Provide an explanation of why the TRA was conducted (i.e. program management's review for maturing technologies, TRA required for a decision point, etc.), and scope of the assessment. Reference applicable decision memos and planning documents.

TRA Process

Provide an overview, and plan of actions and milestones to conduct the TRA. Reference planning documents.

RESULTS

Provide the following for each critical technology assessed:

• Technology Reviewed: Provide a detailed description of the technology that was assessed. The level of detail can vary depending on the phase of development, design characteristics, and scope of review. Organizations should strive to provide a sufficient amount of information to facilitate an understanding of the technology assessed.

• Function: Describe the functions of the critical technologies.

• Relationship to Other Systems: Describe how the critical technologies interface with other systems.

• Development History and Status: Summarize pertinent development activities that have occurred to date on the critical technology.

• Relevant Environment: Describe relevant parameters inherent to the critical technology or the function it performs as it relates to the intended operational environment.

• Comparison of the Relevant Environment and the Demonstrated Environment

Describe differences and similarities between the environment in which the critical technology has been tested and the intended environment when fully operational. The demonstrated environment must correspond to the identified relevant environment for the TRL to be justified.

• Technology Readiness Level Determination

State the TRL determined for the critical technology and provide the basis justification for the TRL.

• Operational Requirement: Describe the required/traceable system functional performance and enabling features for the critical technology elements.

ATTACHMENTS

Include the following planning documents:

- TRA Plan
- Supporting documentation for identification of critical technologies
- Completed tables: TRL Questions for critical technologies
- List of support documentation for TRL determination
- TRL Summary table
- Lessons Learned
- Team biographies

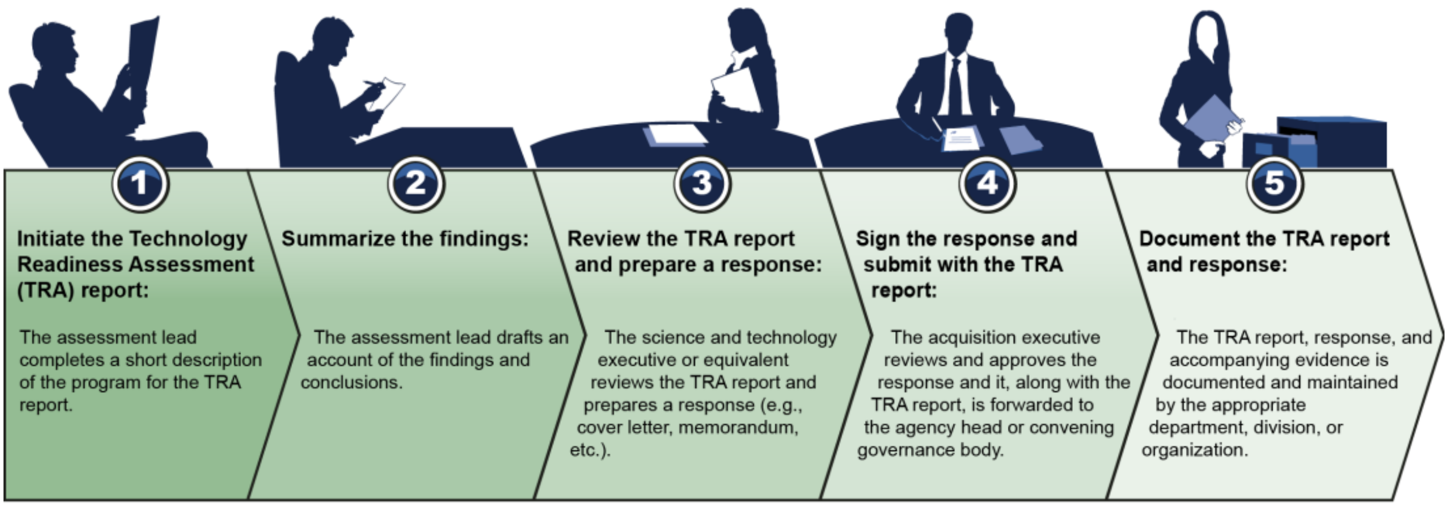
Source: GAO analysis of agency documents. | GAO-16-410G

Steps for Preparing and Coordinating the TRA Report

A TRA report is prepared following an **objective** assessment of critical technologies. The steps described below are focused on the preparation of reports that will be used to certify the readiness of critical technologies at a decision point where involvement of a governance body and multiple levels of review are vital to a report's preparation. Protocol (that is, the roles, responsibilities, authorities, and accountabilities) for developing, validating, and approving the results of a TRA and its accompanying report, as well as terminology, will likely vary between organizations and agencies; however, each should be able to demonstrate equivalency to the process described herein. TRA reports prepared for knowledge-building purposes where maturing technology is the main focus can tailor the process, as appropriate, by modifying or eliminating steps that involve governance bodies' reviews.

In general, the TRA team lead prepares and coordinates the TRA report with detailed input from members of the assessment team before submitting it to the appropriate organizational officials. Figure 11 shows five generic steps to **reliably** prepare, coordinate, approve, and document TRA reports and respond (for example, with a cover letter or memorandum) for a decision point where governance bodies review and certify the results.

Figure 11: Five Steps to Prepare the Technology Readiness Assessment Report



Source: GAO analysis and subject matter expert input. | GAO-16-410G

In step 1, the TRA report draft is started. For this step, the assessment team lead provides and documents the introduction and other descriptive information in the TRA report.

In step 2, the assessment team summarizes the findings along with references to supporting evidence. The evidence may include documented test results or applications of technology, technical papers, reports, analyses, and other artifacts.[27] The report should explain how the material was used or interpreted to make the assessment, and reference the sources (including chapters or pages) of the evidence presented in the report for determining the TRL. Vague or incomplete references to test results or test documents are not sufficient.[28] The summary should explain the function of

[27] Some technologies may be large, sophisticated, or technically complex and, therefore, have voluminous information. Programs should be prepared to provide the necessary documents, and the assessment team should be prepared to list and summarize them in the TRA report, as appropriate.

[28] A TRL should be assigned with full knowledge of the intended operating environment and the derived environment in which the technology is expected to operate. Consequently, in the discussion of the TRL assigned, specific reference should be made to the demonstrated test results in the context of the test environment relative to the relevant environment.

each critical technology at the component, system, and subsystem levels. The TRA report should also explicitly describe the program increments or spiral developments.[29] The report should highlight the assessment of any additional critical technologies identified. Also, it should describe the results of developmental test and evaluation for all critical technologies.

In step 3, the program manager, technology developer, and other key management and technical staff check the factual accuracy of the TRA report, and an executive or senior level manager prepares a response. This response may be a cover letter, memorandum, or another type of document that is appropriate for the organization. For this step, the science and technology executive reviews the report and prepares the response, which may include additional technical information appropriately indicating concurrence or nonconcurrence with the assessment team's findings and TRA report results.[30] The purpose of the response is to document the coordination among the various stakeholders or departments and organizations, and agreement or disagreement with the assessment team's findings, along with supporting analyses for any disagreements. The science and technology executive must certify that they stand behind the results or provide rationale for any dissenting views or differences of opinion. The acquisition executive approves the response and forwards it to the organizational or agency head.[31] If factual accuracies have been compromised—due to new information, misinterpretation of data, etc.—the TRA report is revised with concurrence of all the team members to correct any inaccuracies.[32] An accompanying log should keep an account of

[29]A program increment or spiral development refers to the specific version of the critical technologies being assessed. Critical technologies evolve and mature as knowledge and experience increases. These discrete increments or spiral developments have unique functions, characteristics, and designs that distinguish them from earlier versions. Thus, it is important that these specific efforts be identified in the TRA report.

[30]The science and technology executive is identified because he or she generally has oversight of technology projects entering development early in the acquisition cycle. Agencies or organizations may differ on the executive or senior manager responsible for these technology development projects. In some organizations, these individuals may be a chief scientist, chief engineer, or project director. The terminology will be used to indicate any of these individuals, as appropriate. Agencies and organizations should readily identify them and their roles and responsibilities in their respective TRA processes.

[31]In some organizations, the acquisition executive and the science and technology executive may be the same person, such as the Federal Project Director on DOE projects.

[32]Some organizations have created an additional step in their TRA report processes to account for inaccuracies.

how each issue was addressed and resolved.[33] For TRA reports that are prepared for program managers and technology developers, organizations should modify this step as necessary to exclude governing bodies. However, there should be necessary reviews at the appropriate levels to ensure the information is accurate and credible.

In step 4, the acquisition executive reviews and approves (signs) the response. The TRA report along with the response is forwarded to the agency head or designated authority, or the organization's convening independent review board. This step is not included for TRA reports that are specifically prepared for program managers and technology developers where the information is strictly used for internal management purposes. Appendix VIII provides websites where TRA report examples can be found.

In step 5, the TRA report and the response are documented and maintained by the appropriate organization or department as evidence for future reference by stakeholders and other interested parties. For this step, depending on the complexity of the system and number of critical technologies assessed, completing the report can take anywhere from several days to several weeks after the assessment. A TRA report prepared for governance authorities for a decision point or stage gate review—such as a Milestone B decision for DOD defense programs—should be prepared well in advance of the scheduled time for the decision because of the time needed for review. The time required to prepare the TRA report will depend on the size of the effort, complexity of technology, amount of available technical data to review, and purpose and scope of the review. Reports prepared for simpler technologies take less time, especially if no critical decisions will be based on the scoring discussion of the TRA. Organizations should establish their timelines for submissions by considering their internal review processes, time and resources required, and any policy requirements. The report should give citations and summary descriptions of the salient aspects of the reference documents that are the basis for the answers documented. The assessment team should plan to reference relevant portions of the project's technical assessment reports in developing the TRA report.

[33] The log provides a permanent record of the report evolution and accelerates the final review and concurrence process.

Response to the TRA Report

The program manager prepares a response (via cover letter and memorandum) to indicate agreement or disagreement with the TRA report. The response accompanies the TRA report and is coordinated and signed by the appropriate executive or senior officials, such as a science and technology executive, acquisition executive, or organizational head. The response should indicate agreement or disagreement with the findings of the assessment team and may include other relevant technical information. A formal response is not required if the report is prepared for knowledge-building purposes, where the information will be used for internal program management. Organizations may employ similar strategies so that differences of opinion can be discussed to reach consensus on the assessment findings. TRA reports prepared for knowledge-building exercises should exclude governance authorities from review.

How Dissenting Views Are Documented and Submitted

Dissenting views can occur when the science and technology executive disagrees with the assessment team's findings and conclusions. Differences of opinion are formally documented in the response and are attached to the assessment team's TRA report. Any major disagreement with the assessment team's findings should be briefly and succinctly explained in the response and should include a clear, logical, and rational explanation of the dissenting view and the evidence to support dissent, such as analyses, test documents, and other technical information. In other words, the dissenting view must be evidence-based, **objective**, and well supported by a reliable body of evidence.

In many organizations, the science and technology executive has oversight of technology projects during the early technology development acquisition phase. However, at other organizations, this role may be fulfilled by other officials such as the chief scientist, lead engineer, or program or project manager. Therefore, these individuals should be clearly identified in the review and approval process.

Dissenting views for TRA reports that are prepared for knowledge building purposes do not need to follow a highly structured review process as described above. However, organizations may employ similar strategies so that differences of opinion can be discussed to reach consensus on the assessment findings. While TRAs conducted for program management purposes do not require external oversight by governance bodies, it is still essential that organizations perform the necessary steps and activities to ensure that the information is **objective** and **useful**.

After completion of the TRA report, organizations should provide the appropriate information for inclusion in other key planning and analytical documents, such as technology maturation plans, risk management plans, and cost and schedule assessments.

Best Practice Checklist: Preparing the TRA Report

- Guidance on how TRA reports are to be prepared, including the processes and steps to create them; reporting elements; process for submittal, review and approval, how the results are communicated, and who is involved in the process exist and were followed.
- The TRA report includes the following elements:
  - executive summary
  - program background
  - TRA purpose and scope
  - description of the process for conducting the TRA, including the selection of the critical technologies
  - results of the critical technology assessments
  - supporting evidence for each technology assessed, including references to key test results
  - executive staff approval of the results.
    - If program manager's response to the report does not concur with the results, the reason or reasons are documented.
    - Management checked the factual accuracy of the TRA report.
- The TRA report and response are documented and kept for future reference.
- TRA reports used for governance were prepared in advance of a decision point so there is enough time to review the results prior to the decision.

Chapter 8

Best Practice: Using the TRA Results

Best practice: TRA results provide **useful** information for monitoring the development of critical technologies and informing the larger capital acquisition programs that integrate them. This practice includes how the TRA process and results are used to increase knowledge about the maturity of critical technologies and potential risk areas, including when and how projects should proceed, consideration of alternative technology, and estimating cost and schedule.

The TRA process and report inform governance bodies, program managers, and technology developers about the maturity of technology, specific aspects of development, and potential areas of risk. Credible TRA reports must provide **useful** information that can serve as a source of input for a variety of decision making and program management processes, such as identifying where maturity gaps among critical technologies exist, formulating plans for maturing technologies deciding when and how technology development efforts should move forward, considering back up or alternative technology, and providing input for other decisions such as estimating cost and schedule.

TRA reports may also be used to illuminate potential areas of concern for discussions on how to mitigate potential risks at each phase of development.[34] A widely accepted practice is using the TRA report to develop or update a Technology Maturation Plan (TMP), a planning tool that lays out the necessary steps and actions to bring immature critical technologies to a target TRL or higher maturity.[35] In some instances, the TMP may include parallel, but limited development and testing of alternative technologies, before determining the final selection.

How TRA Reports Are Used

TRA reports are used to inform an assortment of decisions. Governance bodies should use them at key decision points or stage gates to determine if programs that depend on critical technologies are ready to move forward into the next

[34]Mitigating potential risks may be done in a variety of ways, such as in the form of a technology development roadmap, or the Risk Management Plan for an acquisition program/project. Some organizations already have in place a variety of risk management methods and the TRA report may be used as a source of input.

[35]Organizations employ similar methods to mitigate technology risks as part of their own systems engineering or program management processes, such as those used by the DOD and NASA. The TMP is not a replacement for those methods. Rather, it is a planning tool intended to help technology developers and program managers bring immature critical technologies to a target TRL.

stage of development or production and program managers and technology developers can use them as knowledge-building exercises to inform and track their efforts to mature technologies or to consider tradeoffs in light of changes in cost, schedule or program priorities.

TRAs for Governance Decisions

At decision points, governance bodies use TRA reports to certify that critical technologies have reached a prescribed maturity level. Governance bodies are typically made up of one or more senior or executive-level officials, science and technology chiefs, or department heads that review the TRA report and other important information to decide whether critical technologies are sufficiently mature and the program or project that will integrate them is ready to move to the next acquisition phase. Governance bodies certify the TRA results most commonly before decision to formally initiate a program, but they can also utilize them at other decision points depending on the cost, schedule, or technical risk that may warrant their use.[36] At DOD, the Milestone Decision Authority is the governing official who reviews that a technology for use in a major defense acquisition program has been demonstrated in a relevant environment (TRL 6) prior to a Milestone B approval.[37] At DOE, the governing official reviews the TRA results to make sure technologies are at a TRL 6 prior to critical decision point 2 where approval for the project baseline occurs. [38]

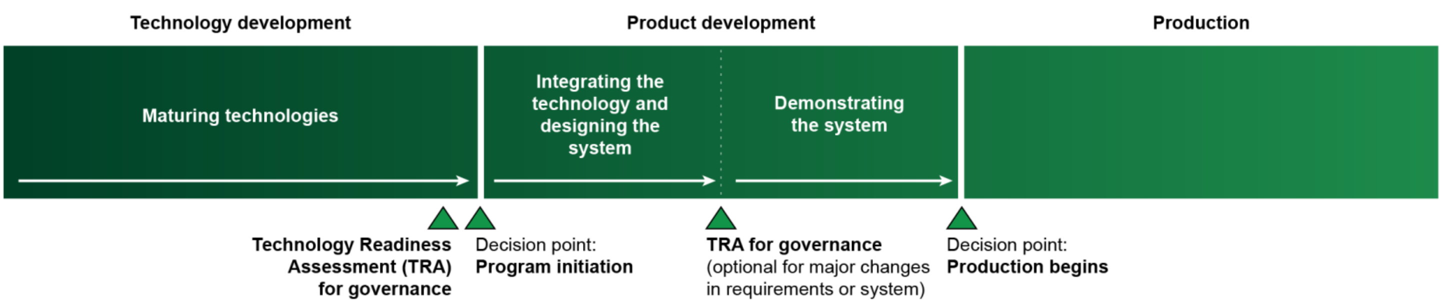
[36]A TRA is not a pass/fail exercise and is not intended to provide a value judgment of the technology developers, technology development program, or program/project office. It is a review process to ensure that critical technologies reflected in a project design have been demonstrated to work as intended (technology readiness) before committing significant organizational resources at the next phase of development.

[37]10 U.S.C. § 2366b. GAO recommends that critical technologies reach TRL 6/7 at the decision point for program initiation. The Under Secretary of Defense for Acquisition, Technology, and Logistics relies on the DDR&E in consultation with DT&E to provide technical advice to support a Milestone B certification. The DDR&E is using the approved TRA process and report as the basis of that technical advice. The law allows the MDA to waive certification requirements (one of which is that the technology in the program has been demonstrated in a relevant environment) if it determines that such a requirement would hinder the DOD's ability to meet critical national security objectives. Whenever the MDA makes such a determination and authorizes such a waiver, the waiver and the reasons for the determination have to be submitted in writing to the Congressional defense committees within 30 days of waiver authorization.

[38]According to DOE, in the next iteration of their guidance, if the total project cost for DOE application exceeds $750M, or the technology system is determined to be a "first-of-a-kind" engineering endeavor, TRL 7 will be recommended to obtain CD-2 approval; otherwise, TRL 6 is acceptable. Currently the guidance suggests a TRL 6 at DC-2, and projects are encouraged to achieve TRL 7 prior to CD-3 as a recognized best practice.

Figure 12 shows a simplified acquisition cycle with notional decision points to highlight where TRAs may be conducted to help inform governance body decision on programs' readiness to proceed. Each organization should determine when and how often TRAs for such purposes should be conducted to accommodate their own requirements, technology considerations, and risk tolerance.

Figure 12: Acquisition Cycle with Technology Readiness Assessments at Decision Points for Governance



Source: GAO analysis of agency documents and subject matter expert input. | GAO-16-410G

TRAs as Knowledge-building Exercises

Technology developers and program managers also use TRA reports to assist them in their day-to-day responsibilities for maturing critical technologies, systems, and sub-systems. These reports are prepared in the interim periods between decision points for building knowledge about the progress of technology maturation efforts, beginning from the early technology development phase—typically where analytical and experimental critical function or characteristic proof of concept occur at TRL 3 through the completion of the system and its qualified test and demonstration at TRL 8. Knowledge-building TRAs can help baseline technology development efforts, inform technology maturation plans, and help monitor progress against those plans. While formal TRA reports are used at key decision points, knowledge building TRAs are not prepared for decision points or stage gates where governance bodies make important decisions that involve organizational resources.[39] Instead, these knowledge building TRAs are used as exercises to make a broad range of decisions including: (1) learning about specific aspects of technology development efforts, (2) deciding whether critical technologies are ready for TRAs for governance authorities at a decision point, or (3) gathering evidence either to continue development efforts or to initiate steps toward using an alternative or backup technology.[40]

Identification of Potential Areas of Concern and Risk

Organizations use TRA reports to illuminate potential areas of concern. The information they provide can facilitate discussions on how to mitigate potential risks, among other important topics. TRAs themselves do not eliminate technology risk nor do they preclude taking risk, but they alert decision makers and others who are interested to potential areas that could be problematic which can guide what actions to take. For example, if the TRA shows critical technologies are mature, the program can proceed as planned. However, if some are immature, a decision could be made to go with a mature substitute or add time and money to accommodate the risks associated with the immaturity. What is unacceptable is to discover immaturity and then proceed with the assumption that maturity will just happen as planned and as scheduled. The TRA report states the TRL determined for each critical technology, at a minimum, and includes the basis for maturity decisions. Decision makers can use this information to identify gaps between the expected TRL and the determined TRL. Aware of potential concerns, organizations may further investigate and analyze the

[39] Peer reviews are used in some agencies to accomplish this interim assessment. During these reviews, the technology development and testing results are evaluated against the TMP to assess the overall progress of technology maturation. Identified issues are documented and tracked to closure throughout the various phases of the project.

[40] The results of TRAs and studies are documented and reviewed to determine the validity of the approach that best meets a project’s goals and its physical, functional, performance, and operational requirements at the best value and include testing and validation of all required functions, including safety. A team consisting of members from the customer, engineering, operations, maintenance organizations, technology development, program management, and selected subject matter experts reviews the documented assessments and study results. The team review focuses on the results of the assessments and studies relative to the alternatives considered, evaluation of systems used to select the recommended design approach, and the potential life-cycle cost savings. The purpose is to review the documented assessment and study evidence to identify the basis for endorsing the selected design approach, including the development and testing of the technology to ensure its maturation in subsequent project phases.

problem raised in order to better understand the potential risks, challenges to development, and potential cost and schedule implications.

Organizations may combine other program management tools with TRAs to help them better understand risk and decide how best to manage and develop critical technologies. For example, DOD has a systems engineering process that specifies analytical methods to help program managers and technology developers in their development efforts. TRA experts have also developed other analytical tools that are designed to work specifically with TRAs to assist program managers and technology developers in maturing technologies. Table 6 lists several program management tools and analytical approaches that can used in combination with TRAs.

Table 6: Example Program Management Tools Used with Technology Readiness Assessments (TRAs)

Name	Description	Purpose
Advancement Degree of Difficulty (AD2)	A predictive method that provides information on what is required to move from one Technology Readiness Level (TRL) to another	Provides technology developers, program managers, and others information in the form of risk (likelihood of occurrence of an adverse event) and impact (cost to ensure that such an event does not occur and the time required to implement the necessary action)
Risk assessment matrix	A process used for understanding the nature, sources, and causes of identified risks for estimating risk level; and for studying impacts and consequences	Helps technology developers, program managers, and others to compare risk analysis results with risk criteria in order to determine whether a specified risk level is acceptable or tolerable. May also highlight the potential cost of assuming or mitigating risks.
Risk Identification, Integration & Illities (RI3)	An Air Force method of identifying frequent risks beyond technology development from “lessons learned” and “best practices” in case studies and Air Force development team experience	Helps technology developers and program managers identify common risks from questions in nine areas: design maturity and stability; scalability and complexity; integrability; testability; software; reliability; maintainability; human factors; and people, organizations, and skills
DOD systems engineering checklists	In technical assessment, DOD’s 18 checklists cover all program phases and supplement the military services’ individual processes and methodologies; the 18 checklists consist of 69 questions in 8 areas—timing at entry level; planning; program schedule; program risk assessment; critical technologies identification; TRA panel; TRA preparation and event; and completion and exit criteria—risk in each question is assessed as red, yellow, green, unassigned, or not applicable	Provides a fact-based understanding of the current level of product knowledge, technical maturity, program status, and technical risk by comparing assessment results against defined criteria; the assessment results allow a better understanding of the health and maturity of a program, giving it a sound technical basis on which to make program decisions

Name	Description	Purpose
Technology Program Management Model (TPMM)	A systems engineering approach to managing early technology development efforts. Developed in 2006 by the Army Space and Missile Defense Command, the tool evolved in partnership with the Defense Acquisition University, and was later sponsored and further developed in 2009 by the Defense Threat Reduction Agency	This tool is intended to help technology developers plan, guide, and measure a program's development maturity; promotes early focus on transitioning technology; acts as a yardstick by providing criteria for evaluating the technology development strategy earlier

Source: Compilation of organization documents | GAO-16-410G

Early Technology Development

A best practice is to conduct TRAs periodically so that organizations can cost effectively mature technologies throughout the acquisition. When used during the early technology phase, before the program initiation phase, TRA results can complement the pursuit of risk reduction efforts to ensure that technology is mature at key decision points. As an activity separate from TRAs prepared for governance authorities, evaluations are typically conducted during the technology development phase to support developmental efforts, including plans for risk reduction efforts. For example, technology developers and program managers may use information gathered via knowledge-building exercises to determine whether technologies are ready to undergo a TRA for governance for an upcoming decision point. In addition, TRA results can be used to

- inform the integrated project team in preparing technology maturation plans for achieving an acceptable maturity roadmap for critical technologies prior to critical milestones decision or stage gates
- provide a basis for modifying the requirements if technological risks are too high
- refine the technology development strategy or similar planning document used in the systems engineering process
- inform the test and evaluation community about technology maturity demonstration needs
- ensure that all potential critical technologies are included in the program's risk management database and plan
- establish technology transition agreements to articulate external dependencies on technology base projects and to define the specific technologies, technology demonstration events, and exit criteria for the technology to transition into the acquisition program

- evaluate whether the criteria in technology transition agreements have been met
- inform cost, schedule, and risk assessment and ensure adequate time and money is set aside to address risks
- consider alternative or back up technology if critical technology development exceeds cost or schedule goals

Organizations should not ignore or dismiss the risks discovered as part of the TRA and proceed with optimism. Multiple pressures within programs and projects encourage this.

A helpful tool is the Army's Technology Program Management Model, which focuses on the technologies during early development.[41] Similar to TRAs that evaluate the maturity of critical technologies, this tool uses TRLs as a basis for measuring technology maturity and incorporates other disciplines to assist technology managers in planning, managing, and assessing technologies for transition. For example, the tool includes systems engineering, transition management, and risk management as part of a core set of activities that can be tailored to the technology development and management goals. Although designed specifically for defense applications, the tool incorporates a number of best practices that can be applied more broadly on other applications. Key characteristics of this tool are that it

- defines each TRL as a phase (stage)
- establishes exit criteria (gate) for each TRL
- reinforces system engineering principles
- aligns to enterprise development process (DOD 5000)
- focuses on transitioning
- provides the criteria supporting technology transition agreements

TRA Process Facilitates Information Sharing Opportunities

TRA's provide many tangible benefits besides an assessment of the maturity of critical technologies at a given time. They include a multitude of activities that require practitioners to cross organizational, professional, and managerial boundaries to establish lines of communication, exchange information, and keep scientists, systems engineers, acquisition officials, and others informed. These activities increase knowledge gathering and facilitate a better understanding of how technologies interact with one

[41] See http://www.tpmm.info for more information.

another and the larger systems into which they are integrated. They create awareness of changes that could affect other elements and systems and elicit involvement and participation of important communities, such as test and evaluation experts during development to ensure that maturity demonstrations adequately stress technologies appropriate to the expected relevant or operational environment. Each TRA also informs a continuous process of improvement and can help identify lessons learned that benefit future TRAs and technology development projects. These lessons learned can be documented within the TRA report or they may be documented separately. In the case of a separate lessons learned document, the TRA report should be referenced within the document and the document should be filed with the TRA report.

Basis for Developing a Technology Maturation Plan (TMP) for Immature Technologies

A practice that has gained wide application is the use of TRA results as a basis to develop or update a TMP—a planning tool that lays out the steps and actions to bring immature critical technologies to a designated TRL or higher maturity. The TMP is discussed in chapter 9. It is important for program managers and technology developers to understand TRAs that report critical technologies at a lower TRL than expected necessitates the need to develop a plan for maturing them to a higher or designated TRL. Organizations may already have similar types of planning tools. They should link TRA reports on critical technologies identified as "immature" to these planning tools to ensure their inclusion in the overall framework for managing risk reduction.

Best Practice Checklist: Using the TRA Results

- TRA results preceded key decision points.
  - The TRA report was used to determine if critical technologies have reached a prescribed maturity.
  - Management ensures that technologies incorporated into major acquisition programs are at least at a TRL 6 or 7 maturity level.
    - If technology is not mature enough, an alternative or backup technology was identified, if appropriate.
- TRA report was used to identify potential areas of concern and risk mitigation efforts.

- Systems engineering team used the results to determine technology maturation plans.
- Critical technologies are included in the program’s risk management plan.
- Lessons learned were documented in the TRA report.
- TRA results were used as input data into cost and schedule risk assessments.

Chapter 9

Best Practice: Preparing a Technology Maturation Plan (TMP)

Best practice: The planning steps and actions necessary to mature critical technologies. The TMP combined with TRAs can be an effective management tool for reducing technical risk and minimizing the potential for cost increases and schedule delays associated with immature technologies.

The TMP is a management planning tool that lays out the steps, actions, and resources needed for maturing critical technologies that have been assessed as less mature than desired or are lagging in maturity compared to other critical technologies. The purpose of the plan is to bring them to a higher or acceptable maturity or readiness level. The TMP uses TRA results and other information for establishing a road map with the necessary development and engineering activities to mature technologies. As such, it provides an effective gauge of the overall progress of technology maturation. The TMP is also useful as a key reference document at a decision point or stage gate to verify that progress has been made in closing the maturity gaps.

Preparing the TMP includes a number of steps such as collecting data for planning and evaluation, determining high level cost and schedule risk, and developing risk handling strategies to provide program managers with a road map to mature technologies.[42] Given that critical technologies may change during development, or technology maturation test results may drive significant design changes, the TMP is intended as a “living” document that should be modified periodically as knowledge increases and as cost and schedule evolve with realistic assumptions about the maturity of critical technologies.

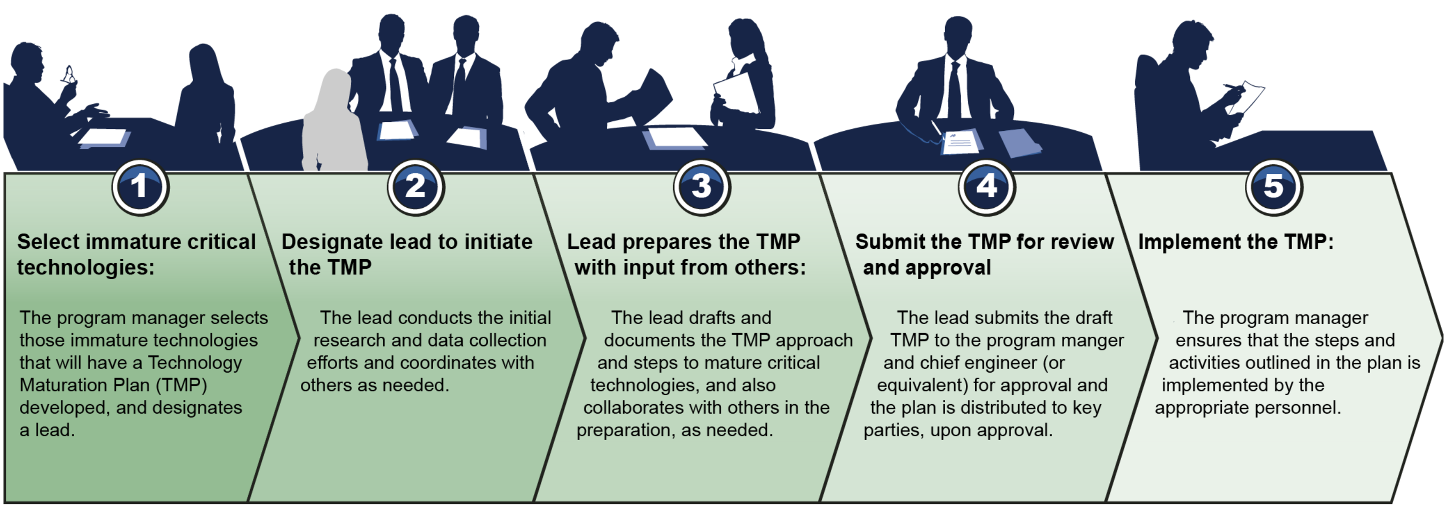
A leading practice involves programs maturing critical technologies during the earlier technology development phase before system development begins. TMPs can be a standalone source of information or part of a broader set of documents, such as a project execution plan or technology development strategy document.

[42] Agencies employ similar methods to mitigate technology risks as part of their own systems engineering or program management processes, such as those DOD and NASA use. The TMP is not a replacement for those methods but is a planning tool specifically designed to help technology developers and program managers bring immature critical technologies to a designated or higher TRL.

Steps for Preparing a Technology Maturation Plan

The TMP has five generic steps to prepare for advancement of critical technologies that have been assessed as immature. The execution of these steps is led by the program manager, who typically designates a lead who has the knowledge to perform and facilitate the necessary work to develop the TMP. Figure 13 shows the five steps. Organizations may tailor them to accommodate their own structures, processes, and policies.

Figure 13: Five Steps to Prepare the Technology Maturation Plan



Source: GAO analysis and subject matter expert input. | GAO-16-410G

In step 1, the program manager acknowledges immature critical technologies cited by the TRA report and designates a lead to prepare the TMP. The program manager requires that a TMP be developed and selects the critical technologies that will have a TMP prepared. These technologies typically have a technology maturity gap. However, other technologies known to have challenges or difficulty during development may be selected as well. For example, a program manager may want a TMP prepared for technologies that pose greater risk due to their complexity or those technologies for which there may be no technological baseline or history from which to draw observations from on past performance.

In step 2, the program managers appoint a lead to the TMP effort that has experience in maturing technology. Additional personnel may be provided to support the effort such as engineering staff, contractor personnel, or subject matter experts, as needed. The designated lead conducts initial research and collects information, starting with the completed TRA report, to prepare the TMP. Initial data collection and research is conducted for each immature critical technology identified from the TRA report. The data collection activities include but are not limited to obtaining the current TRL rating for each critical technology from the TRA report and gathering additional technical assessments or reports, analyses, and test data, if applicable. In addition, the program manager or lead facilitates an assessment of the cost, schedule, and technical risks for achieving the desired TRL for critical technologies. For this step, the lead may be from the program management team or engineering team but should coordinate with others to assist as needed.

In step 3, the designated lead drafts and documents the TMP to mature critical technologies.[43] The TMP should include the approach that will be used to define the technology development activities, the scope of the effort, and steps for bringing critical technologies to the desired maturity. In general, the required technology development activities and specific maturation plans are prepared for each critical technology that the program manager or engineering identifies in Step 1. The lead recruits others as necessary to help develop the approach, activities, and steps for the TMP.

In step 4, the designated lead presents the TMP to the program manager and chief engineer for review and approval. Once approved, the TMP may be provided to other key stakeholders, such as technology developers, governance bodies, or other organizations that have a vested interest in the development of the critical technologies. Depending on their role and responsibilities, they may act as a source to verify the TMP's responsiveness to technology maturity gaps identified in the TRA and the reasonableness of the proposed approach, schedule, costs, and technology risks associated with technology maturation requirements. Once comments are resolved, the program manager proceeds with the next step.[44] For example, the initial documented and approved TMP serves as a baseline and is maintained within the appropriate organization for future reference and updates.

[43]The TMP lead may coordinate with others as needed when drafting and putting the TMP together. The sections that follow contain additional guidance in documenting a plan to mature the technologies, including the TMP template.

[44]The approval process of the TMP is carried out as defined in existing project plans, quality assurance plans or change control and configuration plans, as applicable.

In step 5, the program manager ensures that the steps and activities needed to mature each technology outlined in the TMP are communicated and implemented by the appropriate personnel throughout the organization. The technology developers or project managers are generally responsible for implementing the activities.

Updating a Technology Maturation Plan

The TMP is a "living" document to be updated as progress is made, new information comes to light, or conditions that materially affect the plan ensue. The program manager or designated lead is responsible for monitoring, tracking and making adjustments to the TMP as necessary. If a subsequent TRA triggers an update to the TMP, the program manager establishes a schedule to ensure the update and its completion before the next TRA. The updated TMP serves as a source document as part of a TRA for the assessment team. The four process steps in chapter 6, figure 9 may be tailored to include steps for updating the TMP.

Sections of a Technology Maturation Plan

The TMP has two sections to document information to mature critical technologies: (1) past TRAs and the most current TRLs and (2) a documented plan to mature technologies.

Section 1 of the TMP should describe a review of past technical assessments and any previous assessments that have contributed to the need for the TMP, including previous technology development activities that brought the technology to its current state of readiness. A list of the current TRL for each critical technology is also included in this section.

Section 2 of the TMP should describe the approach, steps, and activities for maturing technologies, including off ramps that consider alternative technologies. Items that should be accounted for include:

- the criticality of the system to mission success or safety;
- the probability or likelihood that the technology will be successful;
- the cost, schedule, and performance penalty incurred if an alternate solution is used (agencies generally include this as part of their risk assessments and document them in the project Risk Register);
- a high level cost estimate of the development strategy; and
- the effects of the strategy on other technical portions of the project.

All of the identified technology gaps and technical assumptions that require resolution or validation should be assessed for impact to the overall system design such that those elements that would require significant redesign, if shown to not perform as expected, are addressed early in the technology maturation process. This allows implementation of alternative approaches and other backup strategies. By including alternative technology solutions in the TMPs, program managers can consider these alternatives if efforts to reach certain TRL goals prove more challenging than expected. For example, if critical technologies become too resource intensive or fall too far behind schedule, program managers can consider backup solutions such as investment trade-offs or the pursuit of backup technologies in lieu of current technology. Case study 5 highlights the importance of establishing plans with backup technology to keep projects on schedule. Advance planning can help program managers respond to unanticipated challenges without compromising performance goals such as cost, schedule, or higher TRLs.

Case Study 5: Identifying Alternative Critical Technologies, *Defense Acquisitions*, GAO-08-467SP

The Navy's P-8A Multi-mission Maritime Aircraft (P-8A), a militarized version of the Boeing 737, entered development in May 2004 with four critical technologies. None of the P-8A's initial four critical technologies were mature when it entered development in May 2004. The program identified mature backup technologies for each of the four, which, according to program officials, would still allow the P-8A to meet minimum requirements. In 2008, the program office reported to GAO that the maturation of critical technologies was on schedule to support the System Development and Demonstration phase. At that time, the program also met and exceeded the cost, schedule, and performance parameters defined in the P-8A acquisition program baseline agreement. The program has since experienced cost growth for reasons unrelated to its critical technologies.

Source: U.S. Navy

***GAO, Defense Acquisitions: Assessments of Selected Weapon Programs*, GAO-08-467SP (Washington, D.C.: Mar. 21, 2008).**

In preparing plans to mature each critical technology, they should identify

- key technology being addressed
- objectives of the technology development
- current state of the art
- the technology development approach
- scope, including
    - specific tasks to be undertaken and
    - results needed for a claimed advancement to a higher TRL
- responsible organization for the maturation activities
- TRL goals for each major milestone
- TRLs to be reached as the project or program progresses through turnover, readiness assessments, startup, and initial operations
- the cost, schedule, milestones, and risks of these activities
- technology alternatives, and
- off ramps that will be taken if results are less than required at each critical decision milestone.

Developing plans to mature critical technologies helps program managers and technology developers mitigate cost, schedule, and technical risks. Many program officers assume that technologies will mature on schedule and meet program requirements. This may obscure program risks and can have significant negative consequences to the overall program.

The Technology Maturation Plan Template

This TMP template shows the detailed elements to include in the plan, along with a description of each element. Organizations can tailor these to accommodate their own terms, definitions, and processes.

INTRODUCTION

Purpose of the Project

Provide a brief summary of the project's mission, status, technology(s) being deployed, etc. During early technology development, the project may be specified or identified. It could be a broad area announcement, a description of a capability gap that the critical technology is being developed to address, or a requirement.

Purpose of the TMP

Describe the objectives and content of the TMP and relate it to the status of the project and any upcoming major milestone reviews.

TECHNOLOGY ASSESSMENTS OF THE PROJECT

Summary of Previous Independent Technical Reviews

Summarize any previous Independent Technical Reviews or other technical assessments that may have contributed to the need for a TRA and the TMP.

Summary of Previous Technology Readiness Assessment(s)

Describe the results of previous TRAs with emphasis on the latest TRA that is driving the TMP. Include the definition of TRLs as used in the TRA. Discuss the critical technologies that were determined for the project.

Technology Heritage

Summarize the previous technology development activities that brought the technology to its current state of readiness. Include discussions of any full-scale deployments of the technology in similar applications.

Current Project Activities and Technology Maturation

Describe ongoing technology development activities (if any) that were initiated prior to the TMP. Completion of these activities should define the starting point for the TMP.

Management of Technology Maturity

Indicate the project office/organizations that will be responsible for managing the activities described in the TMP. Include a brief discussion of key roles and responsibilities.

TECHNOLOGY MATURATION PLAN

Development of Technology Maturation Requirements

Describe the approach used in defining the required technology development activities that will be conducted as described in the TMP. These could include evaluating incomplete questions in the risk assessments, value engineering, or other tools used.

Life-Cycle Benefit

Briefly discuss life-cycle benefits to the project that will result from successful completion of the TMP technology development activities.

Specific TMPs

Maturation plans for each critical technology will be described following the format below for each critical technology that was defined in the latest TRA.

Critical Technology A

- Key technology addressed *(Describe function of the critical technology in the project).*
- Objective *(Succinctly state the objective of the critical technologies)*
- Current State *(Describe current status of critical technology—including TRL assigned in the latest TRA).*
- Technology Development Approach *(Describe the needed technology development work to sufficiently address the maturity gaps, and mature the technology to the next TRL or higher maturity goal. This could include the performing organization, location, etc.)*
- Scope *(Provide a list of the key steps to be taken in performing the work, including a table with milestones, performance targets, TRL to be achieved at milestones or stage gates, and rough order of magnitude of the cost and schedule of development. Include the risks associated with the planned strategy and off ramps/decision points if results are less than expected.)*

Critical Technology B

- Key Technology Addressed
- Objective
- Current State
- Technology Development Approach
- Scope

Critical Technology C (etc., as needed)

TECHNOLOGY MATURITY SCHEDULE *Provide and briefly discuss a high-level schedule of the major technology development activities for each critical technology. Any major decision points such as proceeding with versus abandoning the current technology, selection of a backup technology, etc.*

should be included. Detailed schedules should be given in test plans or used for status meetings during implementation.

SUMMARY TECHNOLOGY MATURITY BUDGET

Present the rough order of magnitude costs to reach a predetermined TRL for each major technology development activity for all critical technologies in the project. Include the total technology maturation costs.

REFERENCES

- **Appendix A**

  Crosswalk of identified previous independent reviews and assessments (if applicable to support information in Section 2)

- **Tables 1, 2, 3, etc.**

  Table(s) for each critical technology, listing of test activities, planned completion date, performance targets, resulting TRL level as each increment of testing is completed, and rough order of magnitude costs.

- **Table X.**

  Technology maturity budget for project

- **Figure 1.**

  Process flow diagram (for technology being assessed)

- **Figure 2.**

  Technology maturity schedule

- **Figure 3.**

  Project execution strategy diagram

Best Practice Checklist: Preparing a TMP for Immature Technologies

- The TMP lays out the steps and actions for maturing critical technologies.
  - A roadmap for maturing technologies was developed.
  - Cost, schedule, and technical risks associated with reaching the desired maturity level for critical technologies have been identified along with potential handling plans including back up technologies.
  - Plans for maturing the integration of the critical technologies are included.

- A high level schedule and budget for maturing each critical technology exists.
- Program manager and chief engineer reviewed and approved the TMP.

- The TMP relies on credible data and analysis and includes the most recently completed TRA report.
- A TMP template identifies what should be addressed in the plan.
- Program managers appointed personnel to the TMP effort who have experience in maturing technology, including engineering staff and contractor personnel and subject matter experts, as needed.
- The TMP is baselined and maintained as a living document that is updated as knowledge increases.

Chapter 10

Practices Are Evolving in Evaluating Software Systems and Systems Integration Using TRAs

NASA introduced TRLs in the 1970s and DOD introduced TRAs in the 1990s; they have been adopted by other agencies and industry, and internationally as effective tools for facilitating understanding and increasing knowledge about the maturity of critical technologies and their readiness for integration into larger acquisition systems. Some experts, however, have argued that existing assessment tools are not well suited to addressing various areas—including software systems and systems' integration. For example, historically, the TRL scale has not always been understood in terms of what needs to be demonstrated when it comes to software at each of the nine maturity levels, since software development did not start until the later phases of the acquisition life-cycle, such as after critical design review. New assessment tools or variations on existing tools have been developed for these areas and others.[45] This chapter briefly describes the current state of practice for evaluating software systems and systems integration using TRA-like tools with a goal of creating awareness and opportunities for advancing knowledge.

Applying TRAs to Software Systems

As indicated earlier in this Guide, software's unique characteristics make it inherently challenging to evaluate compared to hardware. Software is intangible or "invisible," whereas hardware has physical properties and is "visible." The data and information used to measure, monitor, manage, and control is thus inherently different due to the difference in the nature of measuring and evaluating the readiness and performance between hardware and software. Experts who helped to develop this Guide identified several issues that could potentially hamper evaluations of software during the TRA process:

- Software is not routinely considered early in program planning, contributing to its not being identified early as one of the critical technologies.

[45]Guidance for software TRL definitions is in DDR&E, *Technology Readiness Assessment (TRA) Deskbook* (Washington, D.C.: U.S. Department of Defense, July 2009), app. H. See also appendix VI of this guidance for software TRLs.

- A lack of distinction between software types (newly developed software, reused software, and commercial-off-the-shelf software) can obscure whether a technology is critical.
- Definitions are inconsistent as to what identifies new software technology as a critical technology. Reused software code or modified COTS software, for example, can be applied in different applications or platforms that essentially make them new or novel.
- Guidance is lacking for handling technologies that are started in one increment of software but finished in a later increment.

Such challenges are not insurmountable and can be overcome with knowledge, clearly articulated guidance, and personnel with the appropriate expertise, skills, and experience. Experts who helped develop this Guide assert that the following guidelines could help improve and evolve the practice where software is involved

- TRAs should include questions that can help inform software development's progress:
    - How well defined is the intended application? (Leads to how well a problem has been thought through and whether the application of software is defined or ad hoc.) This can identify the difference between what the software does and what it is expected to do.
    - Have artifacts upon which to base decisions about maturity of development been collected as a universal practice when evaluating software?
- Other practices should include asking questions to ensure the management of the evaluation effort appropriately and consistently, such as:
    - Are you following best practices, including documenting your software methodologies and the acquisition life-cycle needs in the software development plan?
    - Are you following a structured or a disciplined process?
    - Are you considering the effects of Agile software development methodologies and their artifacts relative to the acquisition life-cycle, if applicable? For example, a traditional preliminary design review may not be feasible for organizations using Agile software development methodologies.
- The assessment team should include a software engineer to ensure that the right skills, experience, and knowledge are available to evaluate software maturity.

Software Embedded Technologies versus Software-only Technologies

It is important to distinguish between technologies with embedded software and software-only technologies. During the development of this Guide, less knowledge and information were available on TRAs for software-only technologies, largely because embedded software maturity can be judged through hardware demonstrations using existing TRL concepts and definitions whereas similar evaluations for software-only systems are difficult to make due to a lack of physical properties for observation. In addition, in software-embedded systems, where software is in the hardware system, the interfaces are relatively constrained by what the hardware can do or is expected to do. In such cases, the bounds in developing the code are known and the sufficiency of the interfaces may need to be assessed. Software may be captured as a critical technology for a program in several ways. In some cases, programs have selected a new or novel algorithm as the critical technology. An algorithm performs functions such as calculations, data processing, and automated reasoning tasks. In other cases, software elements that enable the functionality of hardware may not be separately identified as a critical, but rather assumed to be part of the hardware subsystem or system.

Software-only technologies, where the software “is” the system and there is no hardware being produced because all commercial components are being used, involve more complicated shorter acquisition life-cycle processes when compared to embedded software systems. In the software-only domain, methodologies typically involve iterative development, with a need to be more agile, involving early planning and incremental testing. In addition, readiness is achieved earlier in software-only systems. For example, the initial architecture level is achieved by the systems requirements review. Such early readiness is possible because unlike an embedded system, the software system does not depend on hardware design decisions. Similarly, the initial design level can be achieved at Milestone B.

Given the complexity of software, opportunity exists to increase knowledge for improving the current state of practice. For example, based on focus group input we received in the development of this Guide, one suggestion is to better identify what is needed to demonstrate certain levels of TRL maturity for software. According to experts, it is not always clear and better descriptions of the kinds of supporting evidence needed to demonstrate certain levels of maturity could improve the practice. While organizations are still learning about how best to evaluate critical technologies for software, we believe that collecting information could help practitioners by identifying lessons learned, establishing best practices, and sharing information with others who are interested more broadly through communities of practice.

Development of System-level Readiness Metrics

Applying TRA methods for evaluating the integration of technologies into a system or the readiness of larger systems or systems-of-systems is another issue that has been debated in the expert community. Many experts believe that a critical technology's integration into a larger system is captured in the higher ends of the TRL scale where a technology must be demonstrated in a system in its proposed operational environment. In addition, there is a general consensus that the TRL for a system as a whole cannot be higher than the least mature technology in that system. During the product development process, TRAs and TRLs can also help expose potential knowledge gaps that can affect system integration. For example, if a project has low TRLs (i.e. less than TRL 6) at its system-level design review , then the project does not have a solid technical basis on which to develop its design and it could be put itself at risk approving a design that is less likely to remain stable.

However, some experts and practitioners have expressed concern about the reliability of TRAs being abstracted from relatively few technologies and applied to a system with multiple technologies. In addition, they argue that TRA methods offer limited insight into system integration, which is one of the primary challenges for development programs. As a result, experts and leading thinkers have proposed alternative approaches to evaluating system readiness, as well as reexamined current ones.

Presented in 2006 by the Systems Development & Maturity Laboratory at Stevens Institute of Technology, the System Readiness Level (SRL) was designed to give a holistic picture of the readiness of complex system of systems by characterizing the effect of technology and integration maturity on a systems engineering effort.[46] The method was proposed because TRLs measure only the maturity of an individual technology and, therefore, does not provide insight into integration between technologies or the maturity of the whole system. The concept of the SRL incorporates the current TRL scale and introduces an integration readiness level (IRL) to calculate a SRL index.

[46] Brian J. Sauser and Jose E. Ramirez-Marquez, *Development of Systems Engineering Maturity Models and Management Tools*, Final Technical Report 2011-TR-014 (Hoboken, N.J.: Systems Engineering Research Center, January 21, 2011).

Similar to TRLs, the IRL is defined as a series of levels that articulate the key maturation milestones for integration activities. Introducing an IRL to an assessment provides not only a check as to where a technology was on an integration readiness scale but also a direction for improving integration with other technologies. Just as the TRL is used to assess the risk associated with developing technologies, the IRL is designed to assess the risk associated with integrating these technologies. Each technology within the system is weighted according to all of its integrations and then rolled up into a single system level. The methodology can be adapted for use in an array of system engineering development efforts and can also be applied as a predictive tool for technology insertion trade studies and analysis.

The United Kingdom Ministry of Defense attempted to develop an SRL methodology to comprehensively examine all subsystems and components of a program. It is used in conjunction with TRL assessments. The SRL self-assessment tool has nine top-level categories: system engineering drivers, training, safety and environment, reliability and maintainability, human factors, software, information systems, airworthiness, and maritime. Each of the nine areas has a set of questions for each of the nine levels of the SRL for a total of 399 questions. Affirmative answers to all questions for a given level determines the SRL for that area. The composite SRL is displayed as a matrix of areas against individual SRLs, resulting in a particular signature at a given point in the program.

The strength of this methodology is its comprehensiveness, which is also its weakness: it is time-consuming to perform and indications are that the Ministry of Defense has discontinued its use. It is worth noting that the Ministry of Defense attempted to use IRLs and design readiness levels before settling on this approach.

The SRL approach has been criticized on the grounds of its being too methodologically complex and that it has not been validated through practice, among other reasons. Some of the experts who helped to develop this Guide believe that the SRL methodology has merit, and a group of experts from government, industry, nonprofit agencies, and academia formed a group called International Systems Readiness Assessment Community of Interest (ISRACOI) in March 2015 for those who have an interest in integration planning and measurement, system readiness measures, and reducing program risk through comprehensive system thinking. A key goal of ISRACOI is to create and maintain a collaborative virtual space populated with systems readiness information, recent research, papers, and presentations. Another goal is to share, disseminate, and maintain relevant artifacts such as the Systems Readiness Assessment Handbook.[47]

Best Practice Checklist: Evaluating Software Systems Using TRAs

- A software development plan exists and is being followed that
  - addresses software methodologies and acquisition life cycle needs, and
  - identifies that a structured and disciplined software development process was used.
- The TRA team includes a software engineer to ensure that the right skills, experience, and knowledge are available to evaluate software maturity.
- TRL maturity for software has been identified with adequate documentation.
- System TRLs are no higher than the least mature technology identified.

[47] For more information about ISRACOI and key initiatives, go to http://www.ISRACOI.org.

Appendix I: Key Questions to Assess How Well Programs Followed the Six Step Process for Developing Credible TRAs

Certain best practices should be followed if credible technology readiness assessments (TRAs) are to be developed. These best practices represent an overall process of established, repeatable methods that result in high-quality TRAs that are **credible**, **objective**, **reliable**, and **useful**. We have identified six steps that, followed correctly, should result in TRAs that governance bodies or program managers can use for making informed decisions.

The following questions relate to each of these six steps and can be used by auditors or other independent entities that may be internal or external to an organization to evaluate the extent to which best practices have been applied.

Step 1 - Design the Overall Technology Maturity Assessment Strategy

1.1 Are the technology needs of a program documented and well-understood? Does the assessment strategy reflects those technology needs?

1.2 Is the TRA aligned with and identified in the assessment strategy in the systems engineering master plan (SEMP) or similar document? Where in the SEMP (or similar document) is technology readiness addressed?

1.2 Did the team develop a master schedule that reflects dates for maturity assessments and decision points? Is the amount of time allotted for the assessment reasonable or is it compressed?

Step 2 –, Define the TRA's Purpose, Develop a TRA Plan, and Assemble the Assessment Team

2.1 Is the purpose and scope of the TRA defined and documented?

2.2 Are the resources, schedule, funding and personnel needed to conduct the TRA identified?

2.3 Is the level of detail for the TRA consistent with the level of detail available for the program?

2.4 Does the TRA plan identify who the recipient of the report will be? That is, will the recipient be the program manager or systems engineer or will it be a governance body in support of an upcoming decision point, stage gate, or go/no-go decision?

2.5 Is the composition of the TRA team informed by the purpose and scope of the assessment?

2.6 Is the TRA team properly sized? What was the basis for the sizing of the TRA team?

2.7 Are the TRA team members independent of the program? Can they maintain objectivity?

2.8 Are the team members experienced in assessing technical maturity? For those team members with assessment experience, what are those experiences? Are the team members' experience, qualifications, certifications, and training documented?

2.9 Did the TRA team have access to additional subject matter experts from a variety of disciplines? If so, who were those experts and in which disciplines were they experienced?

2.10 Is there a written study plan for the TRA? Does it define the evaluation criteria to be used for assessing test results? Does it describe the type of evidence that will be collected to perform the assessment? Who will write the report?

2.11 Is there a plan for handling how dissenting views will be identified? If so, what is the plan?

2.12 Has an approach for documenting the data and reporting the information in the TRA report been defined? If so, what is the approach?

2.13 Was pertinent information obtained to scope and plan the TRA? For example, program master schedule, budget documents, test planning documents.

Step 3 – Select Critical Technologies

3.1 Is there a technical baseline description (TBD) that defines the program requirements? Does the TBD identify the program's purpose, system, performance characteristics, and system configurations?

3.2 Was a rigorous, **objective**, and documented approach, based on the work breakdown structure (WBS) or other key program documents, used to identify critical technology candidates?

3.3 Was the number of critical technologies chosen for assessment based on solid analysis using the WBS, process flow diagrams, or other technical documentation?

3.4 In selecting critical technologies, was the intended operational environment considered? Did this consideration include potential adverse interactions with systems with which the critical technology must interface?

3.5 Were critical technologies selected during early development? Was each critical technology's maturity level evaluated in the program's operational environment?

3.6 Were critical technologies initially selected following a disciplined and repeatable process with defined criteria?

3.7 Was the selection of the critical technologies confirmed using increasingly platform- or program-specific questions and requirements?

3.8 Did the assessment team document the reasons why technologies were selected as critical and why other technologies were not selected?

3.9 Did the subject matter experts who selected and reviewed the critical technologies have appropriate and diverse knowledge?

3.10 When significant program changes occurred, were critical technologies reassessed?

Step 4 – Evaluate Critical Technologies

4.1 Were Technology Readiness Levels (TRLs), or another agreed upon measure, used as a common language among the TRA team, program manager, and governance body?

4.2 Were consistent TRL definitions and evidence needed to achieve the designated level determined before the assessment? Were technologies assessed at TRL 6 or 7 prior to integration into the larger acquisition program?

4.3 Did the assessment clearly define inclusions and exclusions? Did the assessment team evaluate all evidence to support its ratings?

4.4 Did the assessment team interview the testing officials? Did the team verify that the test article and the relevant or operational environment were acceptable? Did the team validate that the test results were sufficient?

4.5 Did the assessment team document all pertinent information related to their analysis? Were credible and verified information (such as schematics, requirements documents, test and analytical reports, and other key information) used as evidence for the assigned TRL? Was the TRL rating of each critical technology documented including a summary, supporting documentation, and justification for the assigned TRL?

4.6 Was the assessment conducted by an **objective** and independent team?

Step 5 – Prepare, Coordinate, and Submit the TRA Report

5.1 Was an official TRA report was prepared that documented actions taken in steps 1-4 above?

5.2 Was there guidance on how TRA reports are to be prepared, including the processes and steps to create them; reporting elements; submittal, review, and approval process; how the results are communicated; and who is involved in the process?

5.3 Was there a TRA template and did it include an executive summary, program background, TRA purpose and scope, process for conducting the TRA, results of the critical technology assessed, and supporting attachments? Was the TRA template used to create the TRA report?

5.4 Were the TRA report and response documented and kept for future reference?

5.5 Were the TRA reports used for governance prepared in advance of a decision point so there is enough time to review the results prior to the decision?

5.6 Does the TRA report include (1) a summary of the findings along with references to supporting evidence for each technology assessed, (2) the results of critical technologies developmental test and evaluation, (3) executive staff approval of the results, and (4) documentation of non-concurrence from the program manager, if applicable? Has management checked the factual accuracy of the TRA report?

5.7 Were official comments on the TRA report obtained and dissenting views explained? Are differences of opinion formally documented and included in the TRA report? Is evidence provided such as analyses, test documents or other technical information to support dissenting views? Is the response to the disagreement clear, logical, and rational?

Step 6 – Use TRA Results and Develop a Technology Maturation Plan

6.1 Was the TRA report used to determine if critical technologies have reached a prescribed maturity? Does management ensure that technologies incorporated into major acquisition programs are at least at a TRL 6 or 7 maturity level? If the technology was not mature enough, was an alternative or backup technology identified?

6.2 Did the program use the TRA report results to develop technology maturation plans for immature technologies? Is the TMP a living document and consistently updated to reflect progress?

6.3 Is there a template for the TMP that includes a roadmap for maturing technologies, cost / schedule / technical risks associated with reaching desired maturity levels, a plan for integrating critical technologies, a high level schedule and budget for maturing technologies, and program manager and chief engineer approval of the TMP?

6.4 Was there a process in place to ensure that TRA results are incorporated into risk management plans and cost and schedule risk assessments?

6.5 Are critical technologies included in the program's risk management plan?

6.6 Were the TRA results used as input data for cost and schedule risk assessments?

6.7 Were lessons learned documented in the TRA report?

Appendix II: Auditing Agencies and Their Websites

GAO frequently contacts the audit agencies in this appendix at the start of a new audit engagement. This list does not represent the universe of audit organizations in the federal government.

Table 7: Auditing Agency Websites

Auditing agency	Agency's website
Air Force Audit Agency	www.afaa.af.mil/
Defense Contract Audit Agency	www.dcaa.mil/
District of Columbia, Office of Inspector General	www.oig.dc.gov/main.shtm
Federal Trade Commission, Office of Inspector General	www.ftc.gov/oig/
National Aeronautics and Space Administration, Office of Inspector General	www.hq.nasa.gov/office/oig/hq
National Science Foundation, Office of Inspector General	www.nsf.gov/oig
Navy, Office of Inspector General	www.secnav.navy.mil/ig
Social Security Administration, Office of the Inspector General	www.ssa.gov/oig/
U.S. Army Audit Agency	www.hqda.army.mil/aaaweb/
U.S. Department of commerce, Office of Inspector General	www.oig.doc.gov/oig/
U.S. Department of Defense, Office of Inspector General	www.dodig.mil/
U.S. Department of Education, Office of Inspector General	www.ed.gov/about/office/list/oig/index.html
U.S. Department of Energy, Office of Inspector General	www.energy.gov/ig/
U.S. Department of Health and Human Services, Office of Inspector General	www.oig.hhs.gov/
U.S. Department of Housing and Urban Development, Office of Inspector General	www.hud.gov/offices/oig/
U.S. Department of Transportation, Office of Inspector General	www.oig.dot.gov/
U.S. Environmental Protection Agency, Office of Inspector General	www.epa.gov/oigearth/
U.S. General Services Administration, Office of Inspector General	www.oig.gsa.gov/
U.S. House of Representatives, Office of Inspector General	www.house.gov/ig/

Auditing agency	Agency's website
U.S. Nuclear Regulatory Commission, Office of the Inspector General	**www.nrc.gov/about-nrc/organization/oigfuncdesc.html**
United States Postal Service, Office of Inspector General	**www.uspsoig.gov/**

Source: Agency websites. | GAO-16-410G

Appendix III: Case Study Backgrounds

We drew the material in the Guide's seven case studies from the seven GAO reports described in this appendix. The table shows the relationship between reports, case studies, and the chapters they illustrate. The table is arranged by the order in the illustrated chapters. Following the table, paragraphs describe the reports and are ordered by the case study number as they appear in the Guide.

Table 8: GAO Reports Used As Case Study in the TRA Guide

Case Study	GAO report	Chapters illustrated
1	GAO-08-408, Defense Acquisitions: 2009 is a Critical Juncture for the Army's Future Combat System	Chapter 2
2	GAO-10-675: Coal Power Plants: Opportunities Exist for DOE to Provide Better Information on the Maturity of Key Technologies to Reduce Carbon Dioxide Emissions	Chapter 2
3	GAO-07-96, Space Acquisitions, DOD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems	Chapter 2
4	GAO-02-201, Defense Acquisitions: Steps to Improve the Crusader Program's Investment Decisions	Chapter 5
5	GAO-08-467SP, Defense Acquisitions: Assessments of Selected Weapon Programs	Chapter 9

Source: GAO reports. | GAO-16-410G

Case Study 1: Immature Technologies Increases Risk, GAO-08-408

The Future Combat Systems (FCS) program—comprised of 14 integrated weapon systems and an advanced information network—was the centerpiece of the Army's effort to transition to a lighter, more agile, and more capable combat force. Congress required the Secretary of Defense to review and report on specific aspects of the program, including the maturity of critical technologies, program risks, demonstrations of the Future Combat System (FCS) concept and software, and a cost estimate and affordability assessment.

Maturing technologies to Technology Readiness Level (TRL) 7 (fully functional prototype demonstrated in an operational environment) prior to starting product development is a best practice and a DOD policy preference. In 2008, GAO has shown that FCS's critical technologies remained at low maturity levels nearly 5 years and $12 billion into development. Accordingly, many of these immature technologies may have an adverse cumulative impact on key FCS capabilities. Insufficient oversight and review was one factor that contributed to the program's subsequent cancellation.

See, *Defense Acquisitions, 2009 Is a Critical Juncture for the Army's Future Combat System*, GAO-08-408, March 2008.

Case Study 2: Assessments Provide Key Information, GAO-10-675

Coal power plants generate about half of the United States' electricity and are expected to remain a key energy source. Coal power plants also account for about one-third of the nation's emissions of carbon dioxide (CO2), the primary greenhouse gas that experts believe contributes to climate change. At the time, regulatory efforts and proposed legislation had sought to reduce CO2 emissions that could have affected coal power plants.

In 2010, GAO has shown that the Department of Energy (DOE) did not use a standard set of benchmarks or terms to describe the maturity of technologies, which limited its ability to provide key information to Congress, utilities, and other stakeholders. This lack of information limited congressional oversight of DOE's expenditures on these efforts, and it hampered policymakers' efforts to gauge the maturity of these technologies as they considered climate change policies.

See, *Opportunities Exist for DOE to Provide Better Information on the Maturity of Key Technologies to Reduce Carbon Dioxide Emissions,* GAO-10-675, June 2010.

Case Study 3: Space Programs Often Underestimate Costs, GAO-07-96

In 2006, GAO has shown that in five of the six space system acquisition programs reviewed, program officials and cost estimators assumed that technologies critical to the programs would be mature and available—even though the programs began without a complete understanding of how long or how much it would cost to ensure technologies could work as intended. For example, on the NPOESS program, DOD and the Department of Commerce committed to the development and production of satellites before the technology was mature—only 1 of 14 critical technologies was mature at program initiation and one technology was determined to be less mature after the contractor conducted more verification testing. This led to significant cost increases and schedule delays.

See, *Space Acquisitions, DOD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems,* GAO-07-96, November 2006.

Case Study 4: Program Updates Can Change Critical Technologies, GAO-02-201

In 1994, the Army began to develop the Crusader, an advanced artillery system consisting of a self-propelled 155-millimeter howitzer and a resupply vehicle. The Army's total acquisition cost in the Crusader program was projected to be about $11 billion.

In 2002, GAO has shown that the maturity of a program's technologies at the start of product development was a good predictor of that program's future performance. Our past reviews of programs incorporating technologies into new products and weapon systems showed that they were more likely to meet product objectives when the technologies were matured before product development started. Additionally, GAO has shown that, based on current Army plans, the Army would begin the Crusader's product development in April 2003 but before maturing critical Crusader technologies to a level considered low risk relative to best practices. These risks related less to whether these technologies could be matured, but more to how much time and cost it would take to mature them. If, after starting product development, the Crusader technologies did not mature on schedule and instead caused delays, the Army may have spent more and taken longer to develop, produce, and field the Crusader system.

See, *Defense Acquisition, Steps to Improve the Crusader Program's Investment Decisions,* GAO -02-201, February 2002.

Case Study 5: Identifying Back-up Critical Technologies, GAO-08-467SP

The Navy's P-8A Multi-mission Maritime Aircraft (P-8A), a militarized version of the Boeing 737, was the replacement for the P-3C. Its primary roles were persistent antisubmarine warfare; anti-surface warfare; and intelligence, surveillance, and reconnaissance. The P-8A shared an integrated maritime patrol mission with the Broad Area Maritime Surveillance Unmanned Aircraft System and the EPX (formerly the Navy Aerial Common Sensor). These systems were intended to sustain and improve the Navy's maritime warfighting capability.

The P-8A program entered development with four critical technologies. Since then, the program removed one critical technology, replaced it two with backups, and added a new critical technology. None of the P-8A's initial four critical technologies were mature when it entered development in May 2004. The program identified mature backup technologies for each of the four, which, according to program officials, would still allow the P-8A to meet minimum requirements. In 2008, the program office reported to GAO that the maturation of critical technologies was on schedule to support the System Development and Demonstration phase. At that time, the program also met and exceeded the cost, schedule, and performance parameters defined in the P-8A Acquisition Program Baseline Agreement.

See, *Defense Acquisitions, Assessments of Selected Weapon Programs,* GAO-08-467SP, March 2008.

Appendix IV: Experts Who Helped Develop This Guide

The two lists in this appendix name the experts in the technology readiness assessment community, with their organizations, who helped us develop this Guide. This first list names significant contributors to the Technology Readiness Assessment Guide. They attended and participated in numerous expert meetings, provided text or graphics, and submitted substantial comments.

Table 9: Experts Who Made Significant Contributions

Organization	Expert
Boeing	Chahriar Assad
Department of Homeland Security, Homeland Security Studies and Analysis Institute	David McGarvey
Department of Homeland Security, Homeland Security Studies and Analysis Institute	Eric Sylwester
Department of Energy, Office of Environmental Management	Hoyt Johnson (retired)
Institute for Defense Analysis	Irv Boyles
Institute for Defense Analysis	David Sparrow
Intrepid Defense Systems	Mike Ellis (retired)
JB Consulting	Jim Bilbro
Lockheed Martin	Bradley Atwater
Lockheed Martin	Joe Uzdzinski
NASA	Faith Chandler
National Science Foundation (Aerospace Corp Fellow)	Phillip Schwartz
Navy - QinetiQ (ONR contractor support on TRAs)	Chris Alberg
Navy, NAVAIR	Ed Copeland, Ph.D.
NexergyTech (DOE contractor)	Jay Roach
Raytheon, Space and Airborne Systems	Matt Markel

Source: Technology Experts. | GAO-16-410G

This second list names those who generously donated their time to review the TRA Guide in its various stages and provided feedback.

Table 10: Experts Who Made Noteworthy Contributions

Organization	Expert
Aerospace Corporation	Phillip Schwartz
Air Force Space and Missile Systems Center (Software Engineering Institute)	Edmund Conrow
Air Force	Ross Anderson
Air Force	Ken Barker
Air Force	Bill Bladygo
Air Force	John Cargill
Air Force	Charles Garland
Air Force	Debbie Grismer
Air Force	Janet Jackson
Air Force	David Karr
Air Force	Matthew Kowalski
Air Force	Claudia Kropas-Hughes
Air Force	Ed Kraft
Air Force	Jim Malas (retired)
Air Force	Col Lester Ogawa (retired)
Air Force	Walt Price
Air Force	Larry Roan
Anser	Joe Goyette
Anser	Michael McGrath
ARCADIS U.S. Inc.	Chris Carson
Army (contractor)	Kevin Meade
Army (contractor)	George Prohoda
Army	Robert Catterall
Army	Willie Fitzpatrick (retired)
Army	Steve Watts
ARTEMIS Innovation	John Mankins
Bell Helicopter	Stuart Retter
Boeing	Jose Alvarez
Boeing	Hitesh Bhadrecha
Boeing	Tom Brackey
Boeing	Ron Burch

Organization	Expert
Boeing	Mark Burgess
Boeing	Michael Ganowsky
Boeing	Matthew Ganz
Boeing	Mike Hill
Boeing	Davoud Manouchehri
Boeing	Eric Miller
Boeing	Roy Okuno
Boeing	Michael Rosenthal
Boeing	John Tracey
Boeing	Charles Woods
Capital Planning Investment Control Solutions	Bill Mathis
Engineering Consultant (formerly with the Air Force)	Gary Stanley
Defense Acquisition University	Jeff Craver
Defense Acquisition University	William Decker
Department Homeland Security	Mark Adams
Department Homeland Security	Doug Drabkowski
Department Homeland Security	Jeanne Lin
Department Homeland Security	Christopher Smith
Department of Commerce	Jillian O'Connell
Department of Defense/University of Maryland	Jacques Gansler (former Under Secretary of Defense of Acquisition, Technology and Logistics)
Department of Defense	Jack Taylor (retired)
Department of Defense (moved to Pratt & Whitney)	James Kenyon
Department of Energy	Mark Arenaz
Department of Energy	Michael Cercy
Department of Energy	David Diddio
Department of Energy	Roland Frenck
Department of Energy	Denise Hill
Department of Energy	Laura Hobgood
Department of Energy	Brian Kong
Department of Energy	Herb Sutter
Department of Transportation	Matt Cuddy
Department of Transportation	Anita Kim
Department of Transportation	David Kuehn
Department of Transportation	Elizabeth Machek

Organization	Expert
Department of Transportation	Ruben Sanchez
Draper Laboratory	Tony Radojevic
GE Aviation	Gene Wiggs (retired)
George Washington University	David Rico
Honeywell Aerospace	Wayne Pearson
Honeywell Aerospace	Bob Rasmussen
Honeywell Aerospace	Bob Smith
HRL Laboratories	Mike Mulqueen
HRL Laboratories	Jeffrey William
Institute for Defense Analysis	Jay Mandelbaum
Institute for Defense Analysis	Paul Kodzwa
Intelligent Systems Technology, Inc.	Dave Zarnow
Jacobs Engineering	Uwe Hueter
Johns Hopkins University	Russell Fink
MCRI	Neil Albert
MCRI	Bill Chadwick
MCRI	Jason Dechoretz
MCRI	Brian Evans
Microsoft	Lewis Shepherd
MIT	Alison Olechowski (doctoral candidate)
MITRE	Alex Chu
MITRE	James Cook
MITRE	Marty Faga
MITRE	Jordan Feidler
MITRE	Marie Francesca
MITRE	Paul Garvey
MITRE	Alfred Grasso
MITRE	Chuck Howell
MITRE	Steve Huffman
MITRE	Lou Metzger
MITRE	Bill Neal
MITRE	Ed Palo
MITRE	Jason Providakes
MITRE	Brigitte Rolfe
MITRE	Linda Rosen

Organization	Expert
MITRE	Brigitta Rubin
MITRE	Lillian Ryals
MITRE	Pete Sherlock
MITRE	Jeff Stevens
MITRE	John Wilson
NASA	Tim Crumbley
NASA	Jim Dempsey
NASA	Neil Dennehy
NASA	Ellen Gertsen
NASA	Steve Hirshorn
NASA	Sharon Jefferies
NASA	John Kelly
NASA	Orlando Melendez
NASA	Steve Noneman
NASA	Jan Rogers
NASA	Stephanie Stilson
NASA	Sandra Smalley
NASA	Joe Smith
NASA	Mike Tinker
NASA	David Voracek
NASA	Kulpa Vygantas
Navy (contractor)	Nazanin Asisan
Navy	Carly Jackson
Navy	Rich Volkert
Navy	Eric Wilson
National Center for Advanced Technology	Mark Gordon
Northrop Grumman	Jerry Nolte (retired)
NSA	Marc Austin
NSA	Robert Cuellar
NSA	Nichelle Dent
NSA	Mark Evans
NSA	Mike Grieco
NSA	David Hillman
NSA (contractor)	Timothy Ingles
NSA	Stephen Letschin
NSA (contractor)	Brian Mack

Organization	Expert
NSA	Stephen Spear
NSA (TASC fellow)	Donald York
National Science Foundation	William Miller
National Science Foundation	Mark Suskin
Office of the Director of National Intelligence	Dave Honey
Potomac Institute	Lee Buchanon
Potomac Institute	Jennifer Buss
Potomac Institute	Patrick Cheetham
Potomac Institute	Eselina Czopla
Potomac Institute	Bob Hummel
Potomac Institute	Alan Meghissi
Potomac Institute	Al Munson
Potomac Institute	Dave Reist
Potomac Institute	Jim Richardson
Potomac Institute	Kathryn Schiller Winston
Potomac Institute	Mike Swetnam
RAND Corp	Cindy Dion-Schwarz
Raytheon	Robert Byren
Raytheon	Steven Cummings
Raytheon	Roberta Gotfried
Raytheon	Rana Lavu
Raytheon	Mercy O'Hoyt
Software Engineering Institute	Michael Bandor
Software Engineering Institute	Mike McClendon
Stevens Institute of Technology/Systems Engineering Research Center, a University-Affiliated Center of the Department of Defense	Arthur Pyster
Stevens Institute of Technology/Systems Engineering Research Center, a University-Affiliated Center of the Department of Defense	Jose Ramirez-Marquez
Stevens Institute of Technology/Systems Engineering Research Center, a University-Affiliated Center of the Department of Defense	Dinesh Verma
SpaceX	Kyle Yang
Teledyne Brown Engineering (moved to Intergraph)	Willie McFadden
Texas A&M University	Jonathan Coopersmith
University of North Texas	Brian Sauser

Organization	Expert
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Source: Technology Experts. | GAO-16-410G

Appendix V: Contacts and Acknowledgments

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Appendix VI: Examples of Various TRL Definitions and Descriptions by Organization

Table 11: DOD Technology Readiness Levels (2011)

TRL	Definition	Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or applications formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	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.
5	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.
6	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.
7	System prototype demonstrated in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring the demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space.
8	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 the true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.
9	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 operational test and evaluations (OT&E). Examples include using the system under operational conditions.

Source: GAO presentation of DOD information | GAO-16-410G.

Table 12: DOD Software Technology Readiness Levels (2009)

TRL	Definition	Description
1	Basic principles observed and reported.	Lowest level of software technology readiness. A new domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms.
2	Technology concept and/or application formulated.	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies using synthetic data.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
4	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 element as appropriate. Prototypes developed to demonstrate different aspects of eventual system.
5	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.
6	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.
7	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.
8	Actual system completed and mission qualified through test and demonstration in an operational environment.	Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenarios.
9	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.

Source: GAO presentation of DOD information | GAO-16-410G.

Table 13: NASA Hardware Technology Readiness Levels (2013)

TRL	Definition	Description
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.

Source: GAO presentation of NASA information | GAO-16-410G.

Table 14: NASA Software Technology Readiness Levels (2013)

TRL	Definition	Description
1	Basic principles observed and reported.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.
2	Technology concept and/or application formulated.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.
4	Component and/or breadboard validation in laboratory environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant environments defined and performance in this environment predicted.
5	Component and/or breadboard validation in relevant environment.	End-to-end software elements implemented and interfaced with existing systems/ simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.
6	System/sub-system model or prototype demonstration in an operational environment.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.
7	System prototype demonstration in an operational environment.	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.
8	Actual system completed and "flight qualified" through test and demonstration.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.
9	Actual system flight proven through successful mission operations.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.

Source: GAO presentation of NASA information | GAO-16-410G.

Table 15: DOE Technology Readiness Levels (2011)

TRL	Definition	Description
1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.
2	Technology concept and/or applications formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants1 and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.

TRL	Definition	Description
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
8	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.	The 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 testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
9	Actual system operated over the full range of expected conditions. Actual operation of the technology in its final form, under the full range of operating conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.

Source: GAO presentation of DOE information | GAO-16-410G.

Appendix VII: Other Types of Readiness Levels

Manufacturing Readiness Levels (MRLs). This measure is used in conjunction with TRLs and it defines risk when a technology or process is matured and transitioned to a system. It is common for manufacturing readiness to be paced by technology readiness or design stability. Manufacturing processes will not be able to mature until the product technology and product designs are stable. MRLs can be used to define manufacturing readiness and risk at the system or subsystem level. For this reason, the MRL definitions were designed to include a nominal level of technology readiness as a prerequisite for each level of manufacturing readiness. As shown, there are 10 MRLs (numbered 1 through 10) that are correlated to the nine TRLs in use at DOD.[48] The final level (MRL 10) measures aspects of lean practices and continuous improvement for systems in production.

Table 16: DOD Manufacturing Readiness Levels

MRL	Definition	Description
1	Basic Manufacturing Implications Identified	This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies.
2	Manufacturing Concepts Identified	This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined military needs. Typically this level of readiness includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.
3	Manufacturing Proof of Concept Developed	This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in Applied Research and Advanced Development. Materials and/or processes have been characterized for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.

[48]For additional information about Manufacturing Readiness Levels, see, Department of Defense, Manufacturing Readiness Level (MRL) Deskbook, May 2011, located at: *www.dodmrl.com/MRL_Deskbook_V2.pdf.*

MRL	Definition	Description
4	Capability to produce the technology in a laboratory environment	This level of readiness acts as an exit criterion for the Materiel Solution Analysis (MSA) Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.
5	Capability to produce prototype components in a production relevant environment	This level of maturity is typical of the mid-point in the Technology Development Phase of acquisition, or in the case of key technologies, near the mid-point of an Advanced Technology Demonstration (ATD) project. Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.
6	Capability to produce a prototype system or subsystem in a production relevant environment	This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the Engineering and Manufacturing Development (EMD) Phase of acquisition. Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes acceptance of a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design has been completed and producibility assessments and trade studies of key technologies and components are complete. Prototype manufacturing processes and technologies, materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a production relevant environment. Cost, yield and rate analyses have been performed to assess how prototype data compare to target objectives, and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment (ICA) for Milestone B has been completed. Long-lead and key supply chain elements have been identified.

MRL	Definition	Description
7	Capability to produce systems, subsystems, or components in a production representative environment	This level of manufacturing readiness is typical for the mid-point of the Engineering and Manufacturing Development (EMD) Phase leading to the Post-CDR Assessment. Technologies should be on a path to achieve TRL 7. System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. Yield and rate analyses have been updated with production representative data. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Manufacturing plans and quality targets have been developed. Production tooling and test equipment design and development have been initiated.
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	This level is associated with readiness for a Milestone C decision, and entry into Low Rate Initial Production (LRIP). Technologies should have matured to at least TRL 7. Detailed system design is complete and sufficiently stable to enter low rate production. All materials, manpower, tooling, test equipment and facilities are proven on pilot line and are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. Cost model and yield and rate analyses have been updated with pilot line results. Supplier qualification testing and first article inspection have been completed. The Industrial Capabilities Assessment for Milestone C has been completed and shows that the supply chain is established to support LRIP.
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	At this level, the system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials, parts, manpower, tooling, test equipment and facilities are available to meet planned rate production schedules. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets have been met, and learning curves have been analyzed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement.
10	Full Rate Production demonstrated and lean production practices in place	This is the highest level of production readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities and manpower are in place and have met full rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

Source: GAO presentation of DOD information | GAO-16-410G.

Integration Readiness Level (IRL). This is a metric to measure the integration maturity between two or more components. IRLs, in conjunction with TRLs, form the basis for the development of the System Readiness Level (SRL). The IRL values range from 0 to 9. The original IRL scale definitions, as proposed by Sauser, have been modified to be consistent with the foundation of the TRL scale and to reflect more closely the NSA development approach. [49] IRLs represent the systematic analysis of the interactions between various integration points. Using IRLs assists the systems engineer in identifying development areas that require additional engineering. IRLs also provide a means to reduce the risk involved in maturing and integrating components into a system. Thus, IRLs supply a common measure of comparison for both new system development and technology insertion. The table below describes the decision criteria for assessing IRLs.

Table 17: Integration Readiness Levels

IRL	Definition	Evidence description
0	No integration	• No integration between specified components has been planned or intended
1	A high-lave concept for integration has been identified.	• Principle integration technologies have been identified • Top-level functional architecture and interface points have been defined • High-level concept of operations and principal use cased has been started
2	There is some level of specificity of requirements to characterize the interaction between components	• Inputs/outputs for principal integration technologies/mediums are known, characterized and documented • Principal interface requirements and/or specifications for integration technologies have been defined/drafted
3	The detailed integration design has been defined to include all interface details	• Detailed interface design has been documented • System interface diagrams have been completed • Inventory of external interfaces is completed and data engineering unites are identified and documented
4	Validation of interrelated functions between integrating components in a laboratory environment	• Functionality of integrating technologies (modules/functions/assemblies) has been successfully demonstrated in a laboratory/synthetic environment • Data transport method(s) and specifications have been defined

[49] Sauser, B., Ramirez-Marques, J., Magnaye, R., Tan, W. (2008). A Systems Approach to Expanding the Technology Readiness Level within Defense Acquisition, International Journal of Defense Acquisition Management, Vol. 1, 39-58.

IRL	Definition	Evidence description
5	Validation of interrelated functions between integrating components in a relevant environment	• Individual modules tested to verify that the module components (functions) work together • External interfaces are well defined (e.g., source, data formats, structure, content, method of support, etc.)
6	Validation of interrelated functions between integrating components in a relevant end-to-end environment	• End-to-end Functionality of Systems Integration has been validated • Data transmission tests completed successfully
7	System prototype integration demonstration in an operational high-fidelity environment	• Fully integrated prototype has been successfully demonstrated in actual or simulated operational environment • Each system/software interface tested individually under stressed and anomalous conditions
8	System integration completed and mission qualified through test and demonstration in an operational environment	• Fully integrated system able to meet overall mission requirements in an operational environment • System interfaces qualified and functioning correctly in an operational environment
9	System integration is proven through successful mission proven operations capabilities	• Fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operational environment • Integration performance has been fully characterized and is consistent with user requirements
Disclaimer: The IRL scale does not attempt to address or account for programmatic lifecycle activities or responsibilities. This scale is intended to be used to assign integration readiness levels based on the applicable definitions and supported by the evidence descriptions.		

Source: GAO presentation of NSA SRA Handbook IRLs. | GAO-16-410G.

System Readiness Levels (SRL). The SRL index is designed as a function of the individual TRLs in a system and their subsequent integration points with other technologies, IRL. The resulting function of this interaction is correlated to a nine level SRL index. This SRL index was defined by the current state of development of a system in relation to DOD's Phases of Development for the Life Cycle Management Framework.

Table 18: System Readiness Levels

Level	SRL definition
9	System has achieved initial operational capability and can satisfy mission objectives
8	System interoperability should have been demonstrated in an operational environment
7	System threshold capability should have been demonstrated at operational performance level using operational interfaces
6	System component integrability should have been validated

Level	SRL definition
5	System high-risk component technology development should have been complete; low-risk system components identified
4	System performance specifications and constraints should have been defined and the baseline has been allocated
3	System high-risk immature technologies should have been identified and prototyped
2	System materiel solution should have been identified
1	System alternative materiel solutions should have been considered

Source: GAO presentation NSA SRA Handbook SRLs| GAO-16-410G.

Appendix VIII: Agency Websites Where TRA Report Examples Can Be Found

Department of Defense: http://www.defense.gov/

Department of Energy: http://www.energy.gov/

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