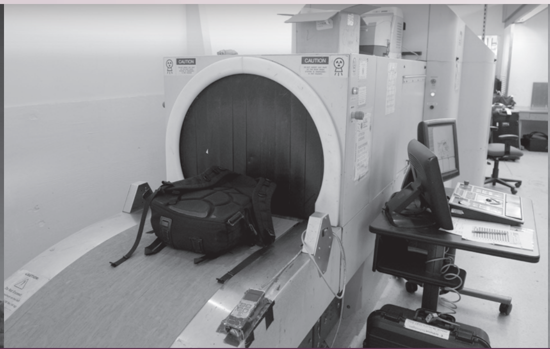
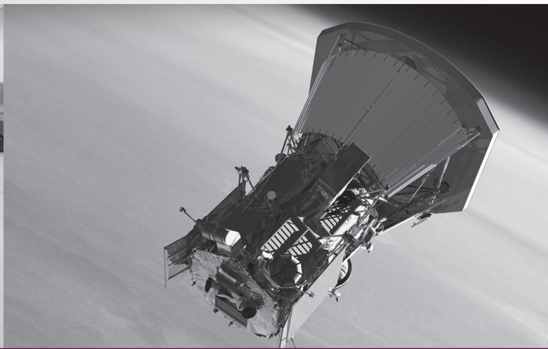
GAO BEST PRACTICES

Technology Readiness Assessment Guide

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





GAO-20-48G
January 2020

GAO
U.S. GOVERNMENT ACCOUNTABILITY OFFICE

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Abbreviations

CDR	Critical Design Review
CT	critical technologies
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EMD	Engineering and Manufacturing Development
IRL	integration readiness level
MDA	Milestone Decision Authority
MDAP	Major Defense Acquisition Program
MRL	manufacturing readiness level
NASA	National Aeronautics and Space Administration
SRA	systems readiness assessment
SRL	system readiness level
TMP	technology maturation plan
TRA	technology readiness assessment
TRL	technology readiness level
WBS	work breakdown structure

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Preface

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 programs 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. For two decades, the U.S. Government Accountability Office (GAO) has shown that using effective management practices and processes to assess how far a technology has matured and how this has been demonstrated are fundamental 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 technologies (hardware, software, and processes) critical to the performance of a larger system or the fulfillment of the key objectives of an acquisition program, including cost and schedule.[1] TRAs, which evaluate the technical maturity of a technology at a specific point in time for inclusion into a larger system, do not eliminate technology risk. But when done well, they can illuminate concerns and serve as the basis for realistic discussions on how to address potential risks as programs move from the early research and technology development to system development and beyond.[2] In addition, TRAs help legislators, government officials, and the public hold government programs accountable for achieving technology performance goals.

[1]In this Guide, we use the term "program," but some agencies may make distinctions between programs, projects, and products. For the purposes of this Guide, these terms can be used interchangeably to accommodate an agency's particular application. The methodology developed in this Guide is intended for use in any acquisition, program, project, or product that benefits from the use of TRAs to evaluate and monitor the maturity of critical technologies.

[2]This Guide refers to "technology development" as the design, development, and engineering of a critical technology or group of technologies, whereas "system development" refers to the design, engineering development, or product development of a system.

This TRA guide (the Guide) is a companion to *GAO's Cost Estimating and Assessment Guide* and the *Schedule Assessment Guide*.[3] With the Guide, GAO is establishing a methodology for evaluating technology maturity based on best practices that can be used across the federal government. This is particularly salient 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 also be made by technology developers and program managers conducting self-assessments (referred to in this Guide as knowledge-building TRAs) during the course of a project to help them evaluate technology maturity, gauge technology development progress, and identify and manage risk. Existing TRA guidance in government agencies and industry may include similar strategies for evaluating technology maturity, but there is no widely held or accepted process for doing so. The science and technology, program management, and systems engineering communities each view technology readiness through their own lenses, which can make for variable results. In addition, some agencies have deemphasized the use of TRAs or questioned their value. We hope that this Guide can reinvigorate the use of TRAs in those organizations.

The Guide is intended to provide TRA practitioners, program managers, technology developers, and governance bodies throughout the federal government a framework for better understanding technology maturity, and best practices for conducting high-quality assessments. 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 other 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, systems engineering, and program acquisition disciplines.

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[3]GAO, *Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs,* GAO-09-3SP (Washington, D.C.: March 2, 2009), and GAO, *Schedule Assessment Guide: Best Practices for Project Schedules*, GAO-16-89G (Washington, D.C.: Dec 22, 2015).

If you have any questions concerning the Guide, you may contact Dr. Timothy Persons at (202) 512-6888 or personst@gao.gov, or Michele Mackin at (202) 512-4841 or mackinm@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 that 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 1990s.[4] This approach has also been embraced by other government agencies, as well as industry in aerospace, maritime, oil and gas, electronics, and heavy equipment that use TRAs to help manage their acquisitions. Relatively 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.[5] This TRA Guide is intended to help fill those gaps.

The Guide has two objectives: (1) to describe generally accepted best practices for conducting high-quality TRAs of technology developed for systems or acquisition programs, and (2) to provide technology developers, program managers, and governance bodies with useful information to more effectively mature critical technologies, determine a technology's readiness, and manage and address risk.[6] 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 processes and best practices of effective TRAs have been followed and whether a TRA demonstrates the characteristics (credibility, objectivity, reliability, and usefulness) of a high-quality assessment. Appendix II lists the key questions to evaluate how well programs have followed the steps and best practices in this Guide.

The Guide recognizes that TRAs have various customers within organizations, such as governance bodies charged with program oversight, as well as more narrow audiences, such as the technology

[4]DOD introduced TRAs in the 1990s. A NASA researcher pioneered the first technology readiness scale in 1974 with seven levels which were not formally defined until 1989.

[5]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 in the product's operational environment.

[6]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 (TMP) resulting from a TRA, described in the section *Technology Maturation Plan,* provides the basis for appropriate risk mitigation actions.

developers, program managers, or systems engineers that use TRAs to determine progress in achieving technology maturity goals. The Guide discusses TRAs in context of the full range of best practices for governance, and also provides information where steps may be tailored for self-assessments, or knowledge-building TRAs, conducted for narrower audiences.

The Guide's chapters first introduce the concept of a TRA, 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 a TRA. It then maps the characteristics of a high-quality TRA, which include credibility, objectivity, reliability, and usefulness, to each of the best practices within the five TRA steps. Specific chapters are devoted to each of the five steps for conducting a TRA, followed by chapters that discuss the preparation of a technology maturation plan (TMP) for technologies assessed as immature, the current state of practice related to the assessment of software intensive technologies, and tools for evaluating system-level readiness, which is an extension of the concept of technology readiness.

The Guide draws heavily from DOD, NASA, and the Department of Energy (DOE) for best practices and terminology. In addition, the Guide draws from 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 conducting 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 (CT) 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.[7]

While this Guide focuses on how to conduct high-quality TRAs from the start of technology development to support technology and product

[7]Critical technologies are technology elements deemed as critical if they are new or novel, or used in a new or novel way, and are needed for a system to meet its operational performance requirements within defined cost and schedule parameters. These technology elements may be hardware, software, a process, or a combination thereof that are vital to the performance of a larger system or the fulfillment of the key objectives of an acquisition program.

development decisions, the expert community recognizes that more frequent, regular self-assessments of the maturity of a project's or program's CTs are also best practices for technology and program managers. However, some experts have been concerned that applying the same set of practices to these more frequent assessments might be 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 demonstrating readiness for product development.

The Guide's Case Studies

The Guide contains a number of case studies drawn from GAO reviews to augment the text. These case studies highlight problems typically associated with technology development efforts, as well as good practices, and emphasize the main points and lessons that the chapters cover. For example, GAO has found that in many programs, cost growth and schedule delays resulted from overly optimistic assumptions about maturing a technology. 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 without available evidence that the technology will perform as expected in its operational environment. Appendix III includes background information for each program used in the case studies.

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 that 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 can inform them of the criteria GAO may use in evaluating their programs. In addition to GAO, other audit organizations including the Inspector General, may also use the criteria prescribed in the Guide for their work. We intend to periodically update the Guide. Comments and suggestions from experienced users, and recommendations from experts in the relevant fields are encouraged.

The Guide’s Approach

To ascertain the generally accepted best practices for conducting high-quality TRAs, we worked with practitioners and technology experts from across the federal government, commercial industry, nonprofits, and academia. We conducted periodic in-person meetings at our headquarters building in Washington D.C., as well as virtual meetings with a community of over 180 experts where we collected information, facilitated focus groups, and elicited feedback on iterative drafts of the Guide’s chapters. To ensure the Guide reflected a broad range of knowledge and viewpoints in order to identify useful information for maturing critical technologies and determine technology readiness and address risk, we consulted with experts from science and technology, systems engineering, nuclear engineering, software and computer sciences, risk management, and acquisition policy and program management disciplines. We released a public exposure draft of the *GAO Technology Readiness Assessment Guide* (GAO-16-410G) in August 2016 for a 12-month comment period. A GAO expert panel made up of representatives from several mission teams adjudicated more than 400 comments from August 2017 to June 2019.

We conducted our work from January 2013 to December 2019 in accordance with all sections of GAO’s Quality Assurance Framework that are relevant to our objectives. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations in our work. We believe that the information and data obtained, and the synthesis of information conducted, provide a reasonable basis for the guidance in this product. We describe our objectives, scope and methodology in detail in appendix I.

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 TRA 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 high-quality TRAs and promotes their use to benefit many agencies in the federal government as well as other organizations in the United States and 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 VII. Additional contacts and acknowledgments are in appendix VIII.

What is a Technology Readiness Assessment?

A TRA is a systematic, evidence-based process that evaluates the maturity of CTs (hardware, software, process, or a combination thereof) that are vital to the performance of a larger system or the fulfillment of the key objectives of an acquisition program.[8] 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 is 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 the final level where the actual operation of the technology is in its final form and proven through successful mission operations. The TRA evaluates CTs at specific points in time for integration into a larger system.

A TRA can be conducted and updated with regular frequency throughout the acquisition or project life-cycle, and there is no pre-determined number of TRAs or time intervals for conducting these evaluations.[9] Similarly, it is not a requirement that each TRA comprehensively consider all CTs. Rather, the key consideration is that each CT 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 a 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 CT maturity concerns.

[8]A technology element is considered a critical technology if it is new or novel, or used in a new or novel way, and it is needed for a system to meet its operational performance requirements within defined cost and schedule parameters.

[9]Certain certifications and determinations are statutorily required to be made prior to a DOD major acquisition program's milestone B decision. The Department of Energy (DOE), Office of Environmental Management, requires that TRAs and technology maturation plans (TMP) be conducted for major projects where new critical technologies are being developed prior to critical decision 2. The DOE also highly recommends these assessments for smaller projects, as well as operations research efforts, such as technology demonstrations that involve the development and implementation of new technologies or technologies in new operational environments.

GAO has found that the readiness of CTs at the start of technology development affects the schedule and cost of developing a product.[10] Therefore, a TRA performed before development begins provides important information for both the technology developer and program manager responsible for the daily management of developing a product and the governance bodies charged with the oversight of an acquisition program.

Overview of Technology Readiness Levels

TRLs are the most common measure for systematically communicating the readiness of new technologies or new applications of existing technologies (sometimes referred to as heritage technologies) to be incorporated into a system or program.[11] TRLs are a compendium of characteristics that describe increasing levels of technical maturity based on demonstrated (tested) capabilities. The performance of a technology is compared to levels of maturity (numbered 1-9) based on demonstrations of increasing fidelity and complexity. Other readiness level measures, for example manufacturing readiness levels (MRL), have been proposed with varying degrees of success and use throughout the life- cycle of a program. [12, 13] Although not exhaustive, appendix V describes other types of readiness levels.

Some organizations have tailored the TRL definitions to suit their product development applications. In general, TRLs are measured on a 1-9 scale, where level 1 generally represents 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,

[10]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 30, 1999).

[11]Heritage technologies are technologies that have been used successfully in operation. These technologies may be used in new ways where the form, fit or function changed; the environment to which they will be exposed to in their new application is different than those for which they were originally qualified; or process changes have been made in their manufacture.

[12]A scale that consists of ten levels designed to assess the maturity of a given technology, system, subsystem, or component from a manufacturing perspective. MRLs provide decision makers (at all levels) with a common understanding of the relative maturity (and attendant risks) associated with manufacturing technologies, products, and processes being considered to meet DOD requirements.

[13]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).

and successfully operated in its intended environment. Figure 1 features the nine TRLs and descriptions that DOD, NASA, and other organizations use. Appendix IV provides additional examples of government agency TRL definitions and descriptions, including those for both hardware and software.

Figure 1: Technology Readiness Levels (TRL)

Technology readiness level (TRL)	Description
1 Basic principles observed and reported	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 analysis of agency documents. | GAO-20-48G

Uses of TRAs

While a TRA uses TRLs as a key measure for evaluating CTs, an assessment is more than just a single number at single points in time. TRAs are a compilation of lower-level assessments that may span several years, depending on the program schedule and complexity of the development. Assessments can help gauge the progress of a technology's development, inform project 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 the Acquisition Program Life-cycle and TRAs

Acquisition programs and projects in many organizations are broadly divided into phases of technology development, product development, production, and operation activities. These phases may be further 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, data analysis, and other assessments to demonstrate that these criteria have been met. During the acquisition life-cycle, TRAs can monitor the progress of maturing technologies and determine how ready a technology is to make a transition from technology development to subsequent phases.

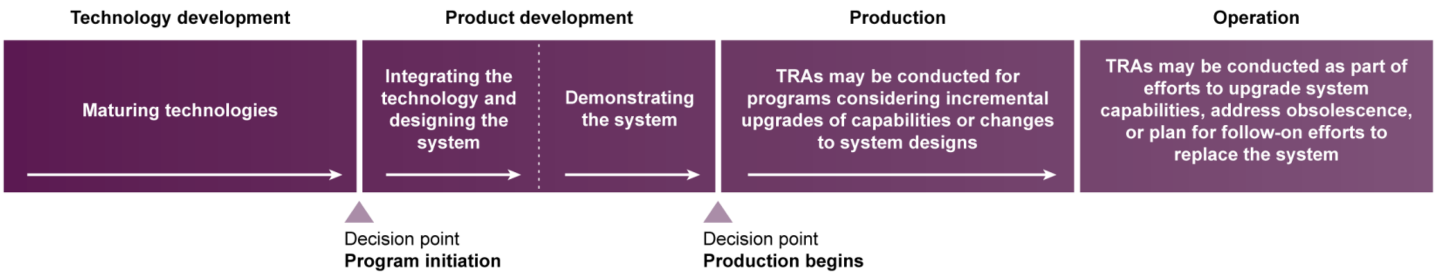
In addition to TRAs, organizations use other types of assessments to examine the technical aspects of acquisition, such as critical design reviews to ensure that a system can proceed into fabrication, demonstration, and tests and the technology can meet the performance requirements within cost and schedule. Other assessments include systems engineering reviews used to examine the integration of components into systems, test reports used to detail the outcomes of developmental tests, and manufacturing readiness assessments used to examine the maturity of the processes that will be applied to manufacture the product.[14] 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 a new or novel solution to a set of needs and requirements that should integrate technologies of varying technology readiness levels into a program or larger system. 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 or heritage technologies for new applications or environments.

Figure 2 depicts a four-phased acquisition process: technology development, product development, production, and operations. 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 the progress in development compared to goals and exit criteria established for the phase.

[14]For some applications, such as the development of complex chemical processing facilities, validation of the performance of all of the technology elements, including critical technologies, in an integrated system is crucial to the technology maturation process. Such comprehensive assessments may use a system readiness assessment (SRA) methodology that provides a systemic understanding of the development life-cycle of the entire system and its interfaces with external entities. Such assessments of the integrated processing system should be completed as part of key TRAs.

Figure 2: Phased Acquisition or Project Life-Cycle with Decision Points



Source: GAO analysis of agency documents. | GAO-20-48G

Since each phase comprises multiple activities, the acquisition or project life-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. Figure 2 is a notional illustration since each organization creates a model that fits the specific types of acquisition processes they use.

The following descriptions highlight characteristics of each phase of the acquisition or project life-cycle and the potential role of TRAs within them.

Technology Development

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. In the technology development phase, the science and technology community explores available technologies (e.g., conceptual systems, components, or enabling technology areas) and matures them to a stage in which they may be able to integrate into a product as part of a formal acquisition program.[15] This typically occurs when the technology reaches at least a TRL 6 and preferably a TRL 7.

When technology is not adequately mature to transition to product development, the program manager should (1) consider using an alternative technology that is mature and that can meet the user's needs, (2) engage the user in a dialogue on appropriately modifying the requirements, or (3) continue to mature the selected technology. In this phase, regular assessments of technology progress provide confidence to the product developers that the technology is advancing towards functioning in a product within available resources of time and funding. Evidence-based documentation may include multiple TRAs that can inform analyses of alternative solutions, or baseline technology strategies, gauge the progress of development efforts, and establish or update maturation plans to increase the likelihood for successful transition of technology into product development.[16] 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 knowledge-building TRA process to select the technology elements that will constitute a system.[17] 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 determine whether this alternative technology might achieve better outcomes.

Product Development

Product development should involve the continued reduction of technology risk, especially as it relates to the integration of technologies into a product or system design. Ideally, product development begins with

[15]Enabling technologies are products of research and development including processes, equipment, and methodologies that facilitate significant gains in performance or capabilities for a particular industry.

[16]Experts recognize that knowledge-building TRAs are cost-effective and useful tools for informing the technology maturation process, which helps limit the more resource-intensive formal, independent TRAs conducted for key decision points or stage gates.

[17]An analytical comparison of the operational effectiveness, suitability, and life-cycle cost of alternatives materiel solution that satisfy an established capability need identified in an Initial Capabilities Document. It focuses on identification and analysis of alternatives, Measures of Effectiveness, schedule, Concepts of Operations, and overall risk. An analysis of alternatives also assesses Critical Technology Elements associated with each proposed materiel solution, including; technology maturity, integration risk, manufacturing feasibility, and technology maturation and demonstration needs.

the transition of mature technologies into the project or system 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, 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 expectations can be met, and demonstrations of manufacturing capabilities to show that the product can be consistently produced within cost, schedule, 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 during this phase can 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.[18] Upon entering product development and therefore having achieved at least TRL 6 (system demonstration in a relevant environment) the CT is now considered beyond the reliance of science and technology investment and is dependent on standard systems engineering development practices to achieve a fully mature status. During the product development process, TRAs are important inputs into systems engineering events, such as a project's preliminary design review and critical design review, and can expose knowledge gaps. If a project has a lower than recommended TRL (i.e., less than TRL 7) by preliminary design review, then the project does not have a solid technical basis of its design and the program could put itself at risk of approving a design that is less likely to remain stable.

Production

The beginning of the production phase marks the point at which the elements of a product—its technologies and design—are sufficiently mature for initial production. 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.

[18]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.

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.

TRAs are not typically conducted during this phase. However, programs considering incremental upgrades of capabilities or changes to system designs to address issues, such as parts obsolescence, may still conduct TRAs.

Operation

The operation phase marks the period of actively using the 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 life of a product is determined by its use and by its materials. Buildings, such as nuclear 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 run from 5-15 years. During the operational phase, products are maintained and may undergo refurbishing or receive upgrades. Obsolescence of technologies (that is, when it becomes 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 operation phase as part of efforts to upgrade system capabilities, address obsolescence, or plan for follow-on efforts to eventually replace the system.

Technology Development Approaches

Not every organization develops or manufactures a unique product to meet its needs. While some organizations may develop new products and establish new programs, they may 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.

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. 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, or similar efforts that provide a significant increase in operational capability, may be managed as separate increments.[19] In an evolutionary acquisition, identifying and developing the technologies necessary for follow-on increments continues in parallel with the acquisition of preceding increments, allowing the mature technologies to more rapidly proceed into the product development phase.

Relationship of TRAs to Program Management and Oversight

TRA data collection efforts may be incorporated as an integral part of systems engineering processes upfront and throughout the development and acquisition of a program. When planned and executed well, TRAs are complementary to existing program management activities, system development efforts, and oversight functions by governance bodies. Many practices needed to produce a TRA are a natural outgrowth of sound systems engineering practices, such as identifying CTs, creating a detailed systems structure, developing a plan for ensuring that CTs are evaluated, collecting evidence of the evaluation, and retaining the results as proof that these processes were undertaken as evidence of progress toward maturity. The program manager for the government and for the contractor, 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 bodies and other decision makers who have responsibility for ensuring that acquisitions are progressing and are ready to move forward past key decision points. For these 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 to help inform their management of the technology development process, then they have already built a knowledge base that can provide persuasive evidence that the technology developers have been diligent and thorough in their examination of the CTs, and that the technologies themselves

[19]Incremental increases in operational capability should be developed based on mature technology and delivered to the user in a useful grouping.

have matured at a pace commensurate with the acquisition phases of the program. In this case, governance requirements might be met by validating a program's existing body of TRA knowledge rather than by conducting a new assessment.

Ways to Tailor TRAs for Different Purposes

The TRA process and the content of an assessment 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 high-quality TRAs throughout the life-cycle, the expert community has recognized that tailored self-assessments are useful to help the narrower audience make decisions about the day-to-day management of technology development efforts.

One such example of a tailored approach is through project self-assessments or knowledge-building TRAs, as part of peer reviews. These knowledge-building TRAs are conducted for the program manager, technology developer, or systems engineer for specific purposes, such as:

- learning about specific aspects of technology development (e.g., identifying gaps in maturity or specific areas that may be challenging);
- calculating progress toward achieving technical performance goals for a specific technology or group of technologies;
- identifying potential concerns and risks;
- gathering evidence to continue development efforts or initiate steps toward using an alternative or backup technology;
- demonstrating and maturing the performance of fieldable technologies or prototypes[20];
- understanding the transition risks when maturing technologies;
- determining whether technologies are ready to transition to new or existing acquisition programs or larger systems; and

[20]A prototype is a physical or virtual model used to evaluate the technical or manufacturing feasibility or utility of a particular technology or process, concept, end item, or system. Prototyping is used in an acquisition program as a tool for risk reduction, technology maturation, identifying and resolving integration risks, controlling manufacturing and sustainability risks, requirements development, and minimizing risks of cost growth due to unknowns in design, assembly and integration.

- deciding whether CTs are ready for a TRA to be conducted for governance bodies at an upcoming decision point.

In cases where organizations seek to accelerate technology development through shorter life-cycles as a streamlined acquisition approach, the less resource intensive knowledge-building TRA may be the practical choice. However, tailoring the TRA process may not be appropriate in other situations. In the case of transition to product development, a decision maker would want to ensure that TRA best practices have been followed before making a major commitment of resources.

More Frequent Evaluations of Technology Maturity

Organizations have learned that more frequent, regular evaluations on the maturity of CTs are a best practice. During the 1990s when DOD and NASA were conducting TRAs, governance bodies used the TRA reports at major decision points to determine whether programs that depend on CTs were ready to move to the next acquisition phase. Organizations have since expanded the use of TRAs and understand that conducting knowledge-building TRAs in the periods between decision points can put technology developers, program managers, and systems engineers in a better position to gauge progress, monitor and manage technology maturity, and identify and manage risks earlier.

Technology Maturity Assessment Strategies

Multiyear acquisition projects that involve the development of highly complex technologies and systems over long periods likely require multiple TRAs as part of an overall system development approach. In such cases, a best practice is to develop a technology maturity assessment strategy that involves identifying all the TRAs to be conducted throughout the acquisition of the system. The technology maturity assessment strategy lays out the broad goals and purposes of the TRAs, including when they may be conducted in the acquisition or project life-cycle, and how many, at a minimum, will be undertaken. The maturity assessment strategy can also include when knowledge-building TRAs should be conducted to serve as waypoints to gauge progress toward achieving specific program goals.

The technology maturity assessment strategy should provide guidance on how stakeholders should achieve consensus on conducting the TRAs. For example, in developing an overall technology maturity assessment strategy, stakeholders should agree on whether one or more formal TRAs will be required to support one or more key decision points or stage gates. This strategy should be included in a program's overall acquisition strategy or equivalent document.

Case study 1 shows how knowledge-building TRAs can inform acquisition strategies.

Case Study 1: Knowledge-Building TRAs Inform Acquisition Strategies, cited in GAO-19-336SP

In 2019, the Navy was determining the acquisition strategy for the Next Generation Jammer Low-Band (NGJ-LB) program and analyzing potential solutions to meet its capability needs. The NGJ-LB is an external jamming pod system that will be fitted on EA-18G Growler aircraft in order to disrupt adversaries' use of the electromagnetic spectrum for radar detection, among other purposes. The Navy is planning to execute the program as a middle tier acquisition. A middle tier acquisition—also referred to as an FY16 Section 804 program—is a program that uses a streamlined acquisition process to rapidly prototype or field capabilities within a 5-year period. One of the factors program officials considered to determine whether the program would move forward as a middle tier acquisition was the technology maturity of critical technologies to be used on the program.

The Navy used a technology maturity assessment process it cited as a best practice to inform the program of any technology maturity concerns prior to it making key decisions about its acquisition strategy. According to the Navy, in October 2018, two demonstration of existing technologies (DET) contracts were awarded to assess maturity of technologies, identify potential materiel solutions, and inform acquisition strategy development. Both contractors were required to provide technology demonstration prototypes and demonstrate technology maturity in a relevant test environment. In July 2019, an independent Navy assessment team conducted technology maturity assessments of both contractors' prototype designs using a process it described as having the rigor and discipline of a TRA. We refer to these types of assessments as knowledge-building TRAs. The team examined contractor self-assessments based on technical work breakdown structures that decomposed the system design to its technical elements and supplemental information from the contractors to perform its assessments. Data from the DET contracts, as well as the independent assessment, confirmed the technology is available to support fielding the NGJ-LB capability. Based in part of the results of these assessments, the NGJ-LB program proposed moving forward as a middle tier acquisition program.

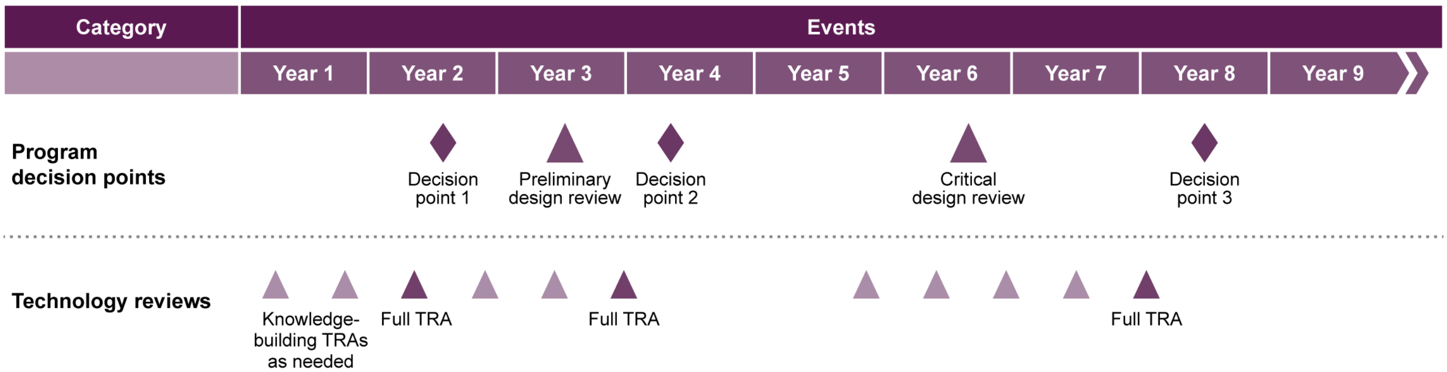
GAO, *Weapon Systems Annual Assessment: Limited Use of Knowledge-Based Practices Continues to Undercut DOD's Investments*, GAO-19-336SP (Washington, DC.: May 7, 2019). Information from subsequent follow up work is included in this case study.

Technology maturity assessment strategies are generally program wide and may encompass years of development and multiple TRAs. Every CT should be included, sometimes multiple times, and the strategy needs to allow for flexibility on how quickly the technologies mature. Often the customer for a technology maturity assessment 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 (MDAP) may not receive a Milestone B decision until the Milestone Decision Authority (MDA) certifies that the technology in the program has been demonstrated in a relevant environment based on an independent review.[21] The strategy should allow for sufficient time and resources to complete the assessment before the expected milestone date.

Figure 3 is a notional program integrated schedule that shows where various TRAs may be conducted in relation to key decision points. Each program manager should determine when TRAs for governance purposes and for knowledge-building purposes will be conducted. The frequency of assessments will vary by program but should include their relation to key decision points; and to other systems engineering activities, such as technical reviews, planned contracting actions (i.e., request for proposal release, source selection activities, and contract awards), production events and deliveries, and key test activities. The number of TRAs for CTs varies depending on their complexity and maturity throughout development. For example, a complex technology entering development at TRL 4 may require more TRAs than a less complex CT entering development at TRL 6.

[21]The Milestone Decision Authority (MDA) is the acquisition executive of a Major Defense Acquisition Program (MDAP) responsible for ensuring that all regulatory requirements and acquisition procedures are in compliance with DOD Instruction 5000.02. The MDA assesses a program's readiness to proceed to the next acquisition phase and determines if a program has met its phase exit requirements and can proceed into the next acquisition phase during a milestone review in terms of cost, schedule, and performance.

Figure 3: Illustration of Technology Readiness Assessments (TRA) in a Program's Integrated Schedule



Source: GAO analysis of agency documents. | GAO-20-48G

Management requirements dictate the timing of required assessments. For example, for DOD MDAPs a TRA is required before a Milestone B decision.[22] However, the strategy should address the entire acquisition life-cycle and reflect the resources (labor, materials, and overhead, among others) 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 technology maturity assessment strategy should include guidance for reaching agreement with stakeholders on the TRA scope, schedule, and resources. Other practices dictate that the program's master schedule should include the general timeframes for conducting the TRAs, and that the amount of time allocated for conducting the assessments be reasonable. Finally, the technology maturity assessment strategy should be aligned with other key planning documents, such as the systems engineering plan.

[22]A Milestone B is the juncture to enter the Engineering and Manufacturing Development (EMD) acquisition phase. It is considered the official start of an acquisition program where major commitments of resources are made. Statutes and DOD policy require documentation, such as a TRA, for Major Defense Acquisition Programs (MDAP). *See,* Weapon Systems Acquisition Reform Act (WSARA), Pub. L. No. 111-23, § 204, 123 Stat. 1704, 1723-24 (May 22, 2009); DoD Instruction 5000.02, at 7, para. 5(c)(3).

Why TRAs are Important and Understanding their Features

Twenty years ago, GAO established 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*, which reported that maturing new technologies before they were included in a product was perhaps the most important determinant of the success of the eventual product.[23] In that report, GAO found that incorporating immature technologies into products increases the likelihood of cost overruns and delays in product development.

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 useful TRA report, program managers, technology developers and governance bodies are in a better position to make informed decisions. GAO found that when program managers and technology developers used 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.

High-quality TRAs provide program managers and governance bodies with important information for making technical and resource allocation decisions on whether a technology 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 report serves as input to other program management decisions to estimate cost, schedule, and risk.

Furthermore, TRAs provide a common language and framework or reference point to facilitate dialogue supported by well-defined measures 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 preparing a technology maturation plan (TMP) for immature

[23] GAO/NSIAD-99-162.

technologies.[24] There are other supplemental methods available that rely on the TRA to help estimate the level of effort needed to mature the technology.[25]

It is worth noting that commercial organizations 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:

[24]The technology maturation plan (TMP) is developed for CTs 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 TRL or goal. 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 concerns, risks, or issues have been satisfactorily addressed or resolved.

[25]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, the 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 and 1 being least difficult to mature the technology (Mankins 2002).The Risk Identification, Integration, and Ilities (RI3) method is an integrated method involving both top-level (key processes) and lower-level (trigger questions) approaches for identifying technology risks. It is intended to support program managers and system engineers in the development and integration of new and reused technologies by identifying the 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.

- 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 both technology development and readiness, and business leaders to ensure both accuracy of the assessment and adequate progression of the technology,
- Relying on mechanisms to change the research plan to accelerate, slow down, or retire the development based upon the technical readiness assessment,
- Ensuring objectivity in the assessment—particularly with regard to demonstration environments—necessitated by system requirement evolution.

TRAs have also expanded their reach within the federal government for research and development projects. In September 2017, the Department of Transportation's Federal Highway Administration issued a guidebook that provides the necessary information for TRL assessments, as a tool for determining the maturity of technologies and identifying next steps in the research process.[26] The department developed the guidebook because it needed a way to identify which research projects to emphasize for transition and which audiences would be interested in the results. See appendix IV where the Department of Transportation TRL descriptions and questions can be found.

TRLs have proven to be reliable indicators of the relative maturity of the technologies reviewed in government and commercial acquisitions, and their eventual success after they were included in product development programs. As discussed in a prior GAO report, DOD and commercial technology development case studies 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.[27] Simply put, the more mature technology is at the start of the program, the more likely the program will succeed in meeting its

[26]U.S. Department of Transportation, Federal Highway Administration, *Technology Readiness Level Guidebook* (Report No. FHWA-HRT-17-047). (Washington, D.C.; Sept. 2017).

[27]GAO/NSIAD-99-162.

objectives. Technologies that were included in product development before they were mature later contributed to cost increases and schedule delays (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		101 percent[a]	120 percent[a]
• Engine	5		
• Rotor	5		
• Forward looking infrared	3		
• Helmet mounted display	3		
• Integrated avionics	3		
Brilliant anti-armor submunition		88 percent	62 percent
• Acoustic sensor	2		
• Infrared seeker	3		
• Warhead	3		
• Inertial measurement unit	3		
• Data processors	3		
Hughes HS-702 satellite		None	None
• Solar cell array	6		
Ford Jaguar automobile		None	None
• Adaptive cruise control	8		
• Voice activated controls	8		

Source: GAO/NSIAD-99-162. | GAO 20 48G.

[a]The Comanche helicopter, 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.

TRAs Help Inform Important Acquisition Functions

In developing this Guide, experts agreed that conducting TRAs provides many tangible benefits in addition to an evaluation of the maturity of CTs at a given time. For example, TRAs may be used to protect program managers from unknowingly accepting or being coerced to accept immature technologies into their programs and projects. Executing the TRA process also 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 increase knowledge and facilitate an understanding of how technologies interact with one another and with the larger systems or programs that integrate them. They may 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 approach 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 2 shows the negative consequences of accepting immature technologies at program initiation when CTs should have been mature.

Case Study 2: Immature Technologies Increase Risk, an Example from DOD, cited in GAO-08-408

Before its cancellation in 2011, the Future Combat Systems—composed from 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 reported 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 3 shows how the absence of key information about the maturity of CTs can hinder important decisions.

Case Study 3: Assessments Provide Key Information, an Example from DOE, cited in GAO-10-675
In June 2010, GAO reported 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 Features of 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 it is important to understand the features that can affect their quality, as well as their limitations. Understanding these features can help both the practitioners who apply the best practices and the decision makers who depend on the TRA report information to better understand context in terms of what is being assessed, and what the information does and does not convey. For example, TRAs are point-in-time evaluations that provide a snap shot in time. 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.

The quality of a TRA depends on close communication among all the stakeholders, including the technology developer, program manager, governance body, and TRA team that performs the assessment. 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. The 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 and disciplines.

Optimism, which is pervasive in acquisition programs, can also affect TRA report findings or their interpretation. For example, program managers may believe that lessons learned from past programs will benefit their program and may not closely scrutinize the maturity of certain technologies. 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 CTs, especially prior to contract award. Case study 4 highlights that underestimating the cost to mature CTs can negatively affect program development and schedule.

Case Study 4: Space Programs Often Underestimate Costs, an Example from DOD, cited in 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 reported 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. 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 System*s, GAO-07-96 (Washington, D.C.: Nov. 17, 2006).

The quality of a TRA is also contingent on the accuracy and relevance of the artifacts, test data, analytical reports, and other information used to support the assessment. The artifacts, data, and other information collected to assess CTs may have dependency, functions, and interaction with other systems or program elements that may be outside the assessment scope or may not be available to the TRA team conducting the assessment. 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 which can 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, technology developers and program managers are in a better position to facilitate and support TRA efforts. Such information, when collected periodically and retained for future reference, can also improve the program management and technology development process.

The Characteristics of a High-Quality TRA and a Reliable Process for Conducting Them

In this section, we introduce the characteristics of a high-quality TRA, the best practices associated with those characteristics, and an established, repeatable process that governs the execution of the best practices. We describe how the process steps, if implemented, can result in a TRA that reflects four distinct characteristics of a high-quality assessment. Finally, we describe how the Guide displays this information by presenting each step as its own chapter with the associated processes and best practices.

Four Characteristics of a High-Quality TRA

GAO's research and discussions with experts from government, industry, non-profits, and academia has found that high-quality TRAs are credible, objective, reliable, and useful. Decision makers—from the technology developer or program manager who sponsors the TRA to the governance body who uses the TRA report to make important resource decisions at a milestone or stage gate—can depend on the information when the report reflect these four characteristics.

- Credible TRAs are conducted with an understanding of the requirements that guide development of the CTs and system, the relevant or operational environment in which it will function, and its integration or interaction with other technologies.
- Objective TRAs are based on objective, relevant, and trustworthy data, analysis, and information; and the judgements, decisions, and actions for planning and executing the assessment are free from internal and external bias or influence.
- Reliable TRAs follow a disciplined process that facilitates repeatability, consistency, and regularity in planning, executing, and reporting the assessment.
- Useful TRAs provide information that has sufficient detail and is timely and can be acted upon.

Best Practices Related to Planning, Executing, Reporting, and Using the TRA

A number of best practices form the basis of a high-quality TRA. Our research shows that credible, objective, reliable and useful TRAs are conducted by government agencies and industry that systematically implements these best practices. The following list describes the best practices that, if implemented, can result in a TRA that exhibits the four characteristics.

A credible TRA

- is comprehensive and includes all of the key information identified in the TRA plan
- identifies and has the expertise needed to conduct the assessment
- considers the newness or novelty of technologies and how they plan to be used as basis for selecting CTs
- considers the operational performance environment and potential cost and schedule drivers as a basis for selecting CTs
- considers the relevant environment as a basis for selecting CTs
- considers the potential adverse interaction with other systems as basis for selecting CTs
- selects CTs during early development
- selects CTs at a testable level

An objective TRA

- is conducted by an independent and objective TRA team
- is based on a level of detail that is consistent with the level of detail (evidence) available
- includes all of the key information (evidence) obtained by the TRA team to conduct the assessment
- is based on solid analysis to determine the number of CTs
- confirms the CTs based on more specific questions and requirements
- is based on test articles and results that have been verified by the TRA team
- assigns TRL ratings based on credible and verified evidence
- is verified by management with respect to the factual accuracy of the TRA report

A reliable TRA

- follows a reliable, disciplined, and repeatable process to select CTs
- is reviewed by the TRA team to ensure the initial TRA plan has all the essential information

- has adequate time and resources to conduct the assessment
- documents the rationale used to select CTs, including technologies not selected
- confirms the TRL definitions are still appropriate, and agreement is reached between the TRA team and the program manager on the kinds of evidence needed to demonstrate that a goal or objective has been met
- has a documented TRA policy or guidance for preparing a report
- includes all the key information in the TRA report
- includes management's written response to the TRL rating in the TRA report including dissenting views
- documents lessons learned in the TRA report

A useful TRA report

- identifies the recipient or recipients of the TRA report
- is used for its stated purpose, such as to inform decision makers about whether a prescribed TRL goal has been met, or identify potential areas of concern or risk, among other purposes.
- identifies the actions to take for CTs assessed as immature, such as considering an alternate or backup technology, developing a technology maturation plan, updating the program risk management plan, or updating the cost and schedule risk assessments
- is submitted in advance of a decision point or stage gate for governance reviews

The Five Step TRA Process

This Guide presents a five step process that provides the framework for planning, assessing, and reporting the TRA. The process represents a consistent methodology based on government and industry best practices that can be used across organizations to assess the maturity of CTs. By following a process of repeatable steps, organizations should be able to produce high-quality TRA reports that can be clearly traced, replicated, and updated to inform decision makers who use the information. Each of the five steps is important for ensuring that TRAs provide decision makers with high-quality information for making important decisions. Figure 4 shows the five steps for conducting a TRA. The subsequent chapters in this Guide have a chapter on each step that describes the process in more detail, and the corresponding best practices for executing them.

Figure 4: Five Steps for Conducting a High-Quality Technology Readiness Assessment (TRA)

Source: GAO. | GAO-20-48G

The TRA Process and Corresponding Best Practices and Key Characteristics

The best practices described in this Guide are mapped to the corresponding steps as part of an overall process for conducting a TRA. When the steps and best practices are followed these efforts can produce a high-quality TRA report. Table 2 shows the five steps for conducting a TRA, the corresponding best practices and associated high-quality characteristics.

Table 2: Five Steps for Conducting a Technology Readiness Assessment (TRA) and Associated Best Practices and Characteristics

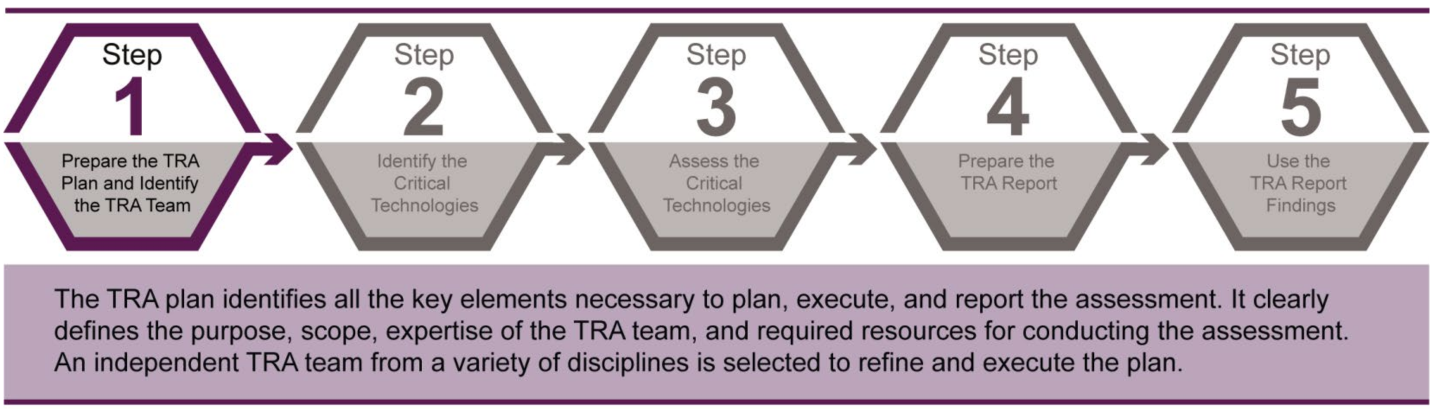
Step	Best practices (Characteristics)
1: Prepare the TRA plan and Identify the TRA team	The TRA plan has a comprehensive assessment approach and includes all the key information. (Credible)
	The TRA plan identifies the recipient or recipients of the TRA report. (Useful)
	The TRA plan identifies the expertise needed to conduct the assessment, and other characteristics of the TRA team. (Credible)
	The TRA team members are independent and objective. (Objective)
	The TRA team reviews the initial TRA plan to ensure it has all the essential information. (Reliable)
	The TRA team has the time and resources to execute the plan. (Reliable)
	The TRA team obtains all the key information to conduct the assessment, such as the program master schedule, budget documents, test plans, and technical baseline description of the program’s purpose, system, performance characteristics, and system configuration. (Objective)
	The level of detail for the TRA is consistent with the level of detail (evidence) available for the program. (Objective)
2: Identify the Critical Technologies	CTs are selected through a reliable, disciplined, and repeatable process. (Reliable)
	CTs are selected based on consideration of the newness or novelty of technologies and how they will be used (Credible)

Step	Best practices (Characteristics)
	CTs are selected based on consideration of the operational performance requirements and potential cost and schedule drivers. (Credible)
	A relevant environment is derived for each CT from those aspects of the operational environment determined to be a risk for the successful operation of that technology. (Credible)
	The potential adverse interaction with other systems which the technology being developed should interface is considered as part of the determination to select CTs. (Credible)
	The number of CTs selected for the assessment is not arbitrary and is based on solid analysis using the work breakdown structure (WBS), technical baseline description, process flow diagram, or other key program documents. (Objective)
	The selection of CTs is confirmed, using more specific questions and requirements that pertain to the platform, program, or system in which they will operate, is confirmed by the TRA team and others, as appropriate. (Objective)
	CTs are selected during early development. (Credible)
	CTs are defined at a testable level, including any software needed to demonstrate their functionality. (Credible)
	The TRA team documents the reasons why technologies are selected as critical, including reasons why other technologies are not selected as critical. (Reliable)
3: Evaluate Critical Technologies	The TRA team confirms the TRL measure and definitions selected in step 1 are appropriate, and reaches agreement with the program manager on the kinds of evidence needed to demonstrate that a TRA goal or objective has been met. (Reliable)
	The TRA team verifies that the test article and the relevant or operational environment used for testing are acceptable and the results are sufficient. (Objective)
	The TRA team assigns a TRL rating for each CT based on credible and verified evidence, such as test and analytical reports, requirements documents, schematics, and other key documents. (Objective)
4: Prepare the TRA Report	Policy or guidance details how TRA reports should be prepared, including a template that identifies the elements to report; process for submission, review and approval; how the TRA report results should be communicated; and who should be involved. (Reliable)
	The TRA report includes all of the key information. (Reliable)
	Management checks the factual accuracy of the TRA report. (Objective)
	The TRA report includes management’s written response to the TRL rating. (Reliable)
5: Use the TRA Report Findings	The TRA report is used for its stated purpose, such as to inform decision makers about whether a prescribed TRL goal has been met, or identify potential areas of concern or risk. (Useful)
	For CTs assessed as immature, one of several actions is identified, such as the consideration of alternative technology, development of a technology maturation plan, updates to the program’s risk management plan, and revision of the cost or schedule risk assessments (Useful)
	TRA reports used for governance purposes are submitted in advance of a decision point or stage gate. (Useful)
	The TRA report documents lessons learned. (Reliable)

Source: GAO analysis and subject matter expert input. | GAO-20-48G.

The five steps for conducting high-quality TRAs can be tailored to meet specific goals. For example, in the case of a knowledge-building TRA conducted as a project self-assessment, a subset of practices from Steps 3 and 5 might be the most relevant. Each chapter will lay out when such tailoring may be appropriate. 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.

Step 1 – Prepare the TRA Plan and Select the TRA Team



Source: GAO. | GAO-20-48G

The program manager or technology developer develops the initial TRA plan. The TRA plan should clearly define the purpose and scope, goal of the assessment, resources to be provided to support the assessment, such as the funding and time to conduct the assessment, how dissenting views will be handled, and for whom the TRA is being conducted. In addition, the TRA plan should describe the system, specify the CT definition and TRL definitions to use, identify potential CTs to evaluate, and identify the expertise needed to select the TRA team members, along with any agreements, such as statements of independence.[28] The level of detail in the TRA plan needs to be consistent with the level of detail (evidence) available about the program.

The TRA should be conducted by a team of knowledgeable individuals who are experienced in assessing technology maturity and their qualifications, certifications, and training should be documented. These team members are often outside the program office, have expertise with

[28]Although the definition of a CT may vary slightly from organization to organization, technology elements are generally considered critical if they are new or novel, or used in a new or novel way, and are needed for a system to meet its operational performance requirements within defined cost and schedule parameters. These definitions should be included in an organization's policy or guidance, and identified in the TRA plan as a key reference for the program manager and TRA team. Similarly, organizations should choose the set of TRL definitions that best suit their needs or application.

the technologies to be evaluated, and bring objectivity and independence to the activities.

Preparing the TRA plan is a twofold process. First, the program manager or technology developer prepares the initial TRA plan to guide the process for conducting the assessment by an independent and objective TRA team. Key information is collected and added to supplement the TRA plan, such as the program master schedule, budget documents, test plans, and a technical baseline description that describes the program's purpose, system, performance characteristics, and system configuration.[29] Second, once the initial plan is drafted and TRA team members are selected, the plan is reviewed by the TRA team to ensure the plan has all the essential information. At this point, the TRA team and the program manager or technology developer may discuss the plan and information to ensure that the assessment approach is sound and understood.

Parts of the TRA plan may be revised, such as the scope, schedule needed to conduct the assessment, funding to support the effort, or increasing personnel to conduct the assessment.

Purpose and Scope of a TRA Plan

As the TRA team refines the plan, a sufficient level of detail for the assessment should be consistent with the level of detail (evidence) available for the expected level of maturity of the CT 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. The TRA should obtain all of the key information (evidence) needed to conduct the assessment to ensure it is objective. The information may include the program master schedule, budget documents, test plans, and technical base description of a program's purpose, system, performance characteristics, and system configuration.

The purpose of a TRA plan falls into one of two categories:

1. a comprehensive assessment of the CTs needed for a decision point or stage gate review for a governance body as evidence of

[29]It is important to evaluate the technical baseline description for adequacy at the earliest phases of planning. Planning documents should have sufficient detail to support identifying the CTs.

demonstrating that a prescribed maturity or criteria for decision making purposes, such as whether to commit resources and approve a program to move to the next phase of development, or

2. a knowledge-building TRA to evaluate the maturity of a certain CT or group of CTs to assess their progress during development.

TRAs conducted as comprehensive assessments would apply the full range of best practices outlined in this Guide. In the case of a knowledge-building TRA conducted for a narrower audience—the program manager, technology developer, or systems engineer—and where more frequent and informal assessments may be conducted, the purpose can vary, including

- learning about specific aspects of technology development (that is, identifying gaps in maturity or areas that may be challenging),
- calculating progress toward achieving a technical performance goal for a specific technology or group of technologies,
- identifying potential concerns and risks,
- gathering evidence to continue development efforts or initiate steps toward using an alternative or backup technology,
- demonstrating and maturing the performance of fieldable technologies or prototypes,
- understanding the transition risks when maturing technologies,
- determining whether technologies are ready to transition to new or existing acquisition programs or larger systems, or
- deciding whether CTs are ready for a comprehensive TRA to be conducted for governance bodies at an upcoming decision point.

The TRA plan should first identify who the customer is and what the needs are for that particular assessment. For example, is the program manager or systems engineer the recipient of the TRA that calculates progress in achieving technical maturity goals for a specific technology or group of technologies? Or is the TRA to be prepared as a formal assessment 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

Once the scope of the TRA has been determined, the TRA team should create a detailed schedule that includes waypoints on when key decisions will be made and provides margins for inevitable (but often unforeseen) delays. It should include a realistic estimate of the time and resources needed to execute the TRA plan considering the number of and rationale for the CTs selected and a realistic schedule for conducting the assessment. In particular, the team should ensure that the TRA schedule is not overly optimistic or based on estimates constructed to meet a particular 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 completion date of the TRA cannot be delayed, then the assessment scope will have to be reduced and discussed with stakeholders and documented.

Essentially, the team should 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.[30] If resources are not available, the team should disclose that the compressed schedule curtails the depth of analysis and may jeopardize the evaluation.

The customers for the TRA plan can 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. Some questions the TRA plan may address are

- What CT definition will be used as criteria to determine which technology elements are critical and how will they be selected?
- What set of TRL definitions will be used as criteria to conduct the TRA?
- 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 evaluation points will be needed to support the assessment?

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[30]GAO, *GAO Schedule Assessment Guide*, GAO-12-120G (Washington, D.C.: May 30, 2012).

- What kinds of evidence will be collected?
- Who will lead the TRA team?
- How will dissenting opinions on the results of the TRA report be handled?
- Will statements of independence be used for members of the TRA team?
- How should the credentials and experience of team members be documented?
- What documentation will be needed for each CT?
- Who will write the TRA report that summarizes the assessment results?
- How will the team communicate with the program?

The scope should also include measures that the team has agreed upon to describe or quantify results of the TRA. For example, the TRA plan should identify the CT definition that will be used as a basis for selecting critical technology elements. In addition, the TRA plan should include the specific set of TRL definitions to describe the criteria for evaluating each CT. In addition, the TRA team should reach consensus on the tools they will use to conduct the TRA, such as checklists or automated checklists or spreadsheet calculators.[31] Importantly, the TRA team should agree on the specific standards to determine the sufficiency of evidence. For example, is direct observation of current 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?

Review of past TRAs conducted on heritage technologies can inform and strengthen current TRA planning efforts, particularly if those same technologies are being used in new ways where the form, fit or function may be different; or in different operational environments. In such cases, it is a good practice to include information about the heritage technology's

[31]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 should be reviewed and approved by the TRA team and the appropriate program or project management officials.

prior mission and purpose, and design changes that have occurred since it was originally developed, among other information.

When scoping the TRA, it is important to note that a one size fits all approach is not realistic. Hardware and software technology frequently vary in complexity and size, thereby making each effort to scope the TRA unique. Each technology may be distinctive and the TRA plan should be tailored to reflect these technological differences.

Selection of the TRA Team

An independent TRA team consists of subject matter experts from a variety of disciplines who will identify or affirm the selection of CTs, evaluate the maturity of those CTs, and assign the TRL rating for each CT assessed. The TRA team, usually recruited by the program manager or other decision making authorities, is also responsible for planning, executing, and documenting the TRA. In this regard, the TRA team should have access to program and contractor personnel, and the data and information to conduct the assessment. The TRA team should participate in a pre-assessment orientation that includes a technical overview of the program and the technologies to be evaluated.

The planning documents and the TRA plan should provide information on the makeup of the team, including biographies detailing the credentials of each member along with information about their experience, qualifications, certifications, and training. In particular, the information should allow someone relying on the assessment to observe that the team can be objective in its evaluation, is independent of the program, and understand how the individual TRA team members were selected.

The number of individuals appointed to the TRA team depends on the purpose of the assessment, the requirements imposed by a governance or oversight body, and the breadth of subject matter knowledge needed for the assessment. Generally, a TRA 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.

For comprehensive TRAs conducted in preparation for a decision point, the governance or oversight body often requires that members of the TRA team be subject matter experts who are independent of the program to avoid conscious or subconscious bias, or the perception thereof. That said, much of the value of the process is in the detailed discussion that leads to assignment of a TRL rating, and including program office team members as observers can be valuable. For knowledge-building TRAs conducted for program managers or technology developers, project team members may be a more practical choice to conduct the assessment. However, maintaining objectivity when evaluating the evidence is a key requirement that should be observed by all members of the TRA team.

In the selection of the TRA team, it is important to

- Ensure that TRA leads, subject matter experts, and practitioners have the relevant experience, knowledge, and training 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 CTs from multiple technological fields, the team will generally be larger than if there are only a few CTs from related fields.
- For a successful independent assessment, technical experts should be selected from outside the program. Typically, an independent TRA team is convened and bases its evaluation of the CT on primary source documentation provided by the program manager. Independent TRA team members may be selected from
    - laboratories or other research entities independent of the project,
    - federally funded research and development centers,
    - subject matter experts within the agency or academic institutions, but not the program, or
    - retired personnel.

The TRA team should have access to additional subject matter experts once the assessment is underway because it not uncommon for teams to discover that they have limited knowledge or depth of experience in certain areas. In this regard, the TRA team should discuss this possibility with the program manager or responsible party so that they can plan accordingly.

The availability of TRA team members with the necessary expertise may be limited or in short supply in some organizations, disciplines, or industries due to limited availability of subject matter experts, cost considerations, or other factors. In these circumstances, it may be impracticable to select members who are entirely independent of the program, and it may be necessary to establish a review board that can independently and objectively review the TRA team's approach, the findings and conclusions reached, or any disagreements among parties. The review board can serve as the independent governance body in the TRA process to ensure that the assessment exhibits all of the high-quality characteristics. 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 TRA team, arbitration can be documented and, along with the evidence on both sides of the disagreement, presented to the governance body.

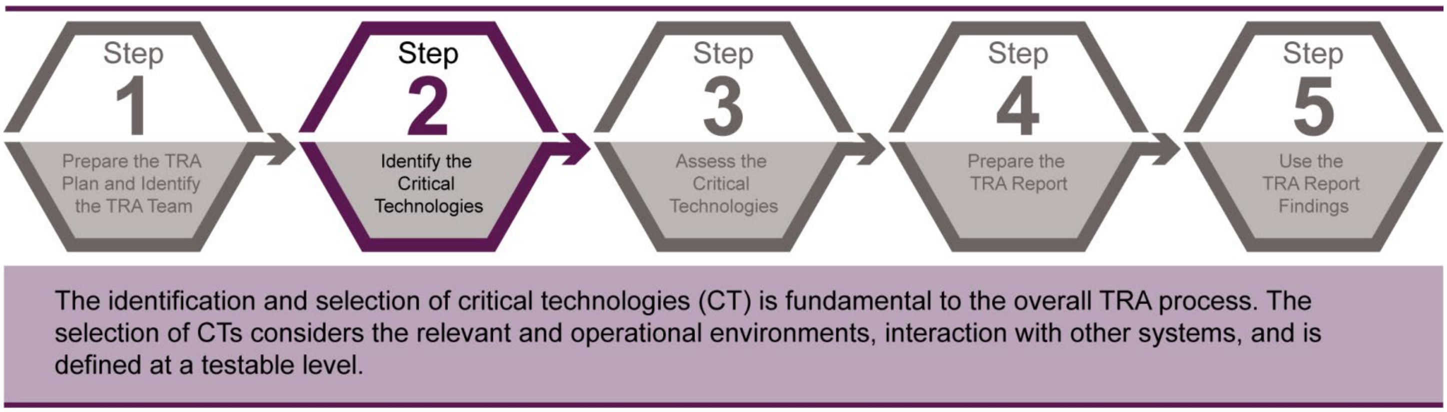
A best practices checklist that includes the corresponding high-quality characteristics related to developing the TRA plan and selecting the TRA team is included below.

Best Practices Checklist: Develop the TRA Plan and Select the TRA Team

- The TRA plan includes a comprehensive assessment approach with the following key information: (Credible)
    - A clearly defined purpose and scope;
    - The resources, schedule, funding, and personnel;
    - The CT definition and TRL definitions for selecting and assessing critical technologies;
    - Evaluation criteria for assessing the test results, the types of evidence needed to perform the assessment, and the person responsible for writing TRA report;
    - A written study plan to help each TRA team member prepare for conducting the assessment; and,
    - A plan for handling dissenting views.
- The TRA plan identifies the recipient or recipients of the TRA report, such as the technology developer, program manager, systems engineer, or governance body. (Useful)
- The TRA plan identifies the expertise needed to conduct the assessment, and other characteristics of the TRA team. These include: (Credible)
    - Composition of the expertise, knowledge, and experience needed to conduct the TRA is clearly written to guide the selection of TRA team members;
    - Size of the TRA team is defined and is adequate to conduct the assessment;

- TRA team members have the requisite experience, qualifications, certifications, and training; and
  - TRA team member profiles are documented and include signed statements of independence
  - TRA team has access to additional subject matter experts from a variety of disciplines, as needed and determined by the team.
- TRA team members are independent and objective. (Objective)
- TRA team reviews the initial TRA plan to ensure it has all the essential information. (Reliable)
- TRA team has adequate time and resources to execute the TRA plan. (Reliable)
- TRA team obtains key information to conduct the TRA, such as the program master schedule, budget documents, test plans, and a technical baseline description that describes the program's purpose, system, performance characteristics, and system configuration. (Objective)
- The level of detail for the TRA is consistent with the level of detail (evidence) available for the program. (Objective)

Step 2 – Identify the Critical Technologies



Source: GAO. | GAO-20-48G

Establishing a disciplined and repeatable process to identify and select CTs is paramount to conducting a high-quality TRA. Selecting CTs during early technology development before product development is a best practice. Subject matter experts with key knowledge, skills and expertise are necessary to accurately evaluate elements of the system or architecture design and the operating environments and subsequently identify the enabling CTs. Technologies identified as critical may change as programmatic or mission-related changes occur, system requirements are revised, or if technologies do not mature as planned.[32]

Critical Technologies Defined

Technologies are considered critical if they are new or novel, or used in a new or novel way, and needed for a system to meet its operational performance requirements within defined cost and schedule parameters.

[32]There are multiple reasons why CTs 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—these may cause significant cost increases and schedule growth. In such cases where changes occur in architecture, component, or technology, an additional TRA that target the changes may be warranted.

Government agencies, such as DOD and DOE use similar definitions.[33] DOD developed the most common definition of CTs, but organizations have adopted or modified the definitions to suit their particular needs. According to DOD, in general, technologies may also 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 CTs when they have longstanding history, knowledge, or familiarity with heritage technologies that have been successfully used in operation. This is problematic in terms of cost increases, schedule delays, or technical performance problems when these technologies are reapplied in new ways where the form, fit or function may be different. The same is true when the environment in which the technology will be operated in its new application differs from which it was originally qualified.

Case study 5 illustrates that officials risk overruns in cost and schedule and can encounter performance shortfalls when they fail to identify all CTs for programs with which they have had experience.

[33]Department of Defense, Assistant Secretary of Defense for Research and Engineering, *DOD Technology Readiness Assessment Guidance* (Washington, D.C.: 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 (Washington, D.C.: Oct. 12, 2009).

Case Study 5: Program Updates Can Change Critical Technologies, an Example from DOD, cited in 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).

Correctly identifying and selecting CTs can prevent wasting valuable resources—funds and schedule—later in the acquisition program. There should be no limitations on the number of CTs, but if an overly conservative approach is used and CTs are over-identified, resources can be diverted from those technologies that require an intense maturation effort. However, the under-identification of CTs because of a real or perceived limitation on the number of CTs allowed may prove disastrous in that such areas may fail to meet requirements, resulting in overall system failure. In addition, the under-identification of critical technologies may result in a poor representation of the number of interfaces or integration needs which are one of the significant causes of system failures.

Considerations in Selecting Critical Technologies

While the process to collect evidence for identifying CTs can be straightforward, the determination for what constitutes a CT requires knowledge, experience, and due professional care. For example, professional judgements need to be made about what a technology is, what makes a technology critical, and at what level (e.g., subcomponent, component, system, or element) it is appropriate to test, demonstrate, and affirm key functions of that technology. Many CTs at the subcomponent or subsystem level may consist of multiple technologies made up of hardware with embedded software. Some organizations, such as DOE, may define a CT as a 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 CTs 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 to help identify CTs. Case study 6 illustrates the importance of how narrow definitions can affect the selection of CTs for assessment.

Case Study 6: Narrow View of Critical Technologies Can Result in the Underrepresentation of Technical Risks, an Example from DOD, cited in GAO-18-158

The Navy's Columbia class ballistic missile submarines will replace the 14 Ohio class that currently provide the sea-based leg of the U.S. nuclear triad, slated to begin retiring in 2027. Additional development and testing are required to demonstrate the maturity of several Columbia class submarine technologies that are critical to performance, including the Integrated Power System, nuclear reactor, common missile compartment, and propulsor and related coordinated stern technologies.

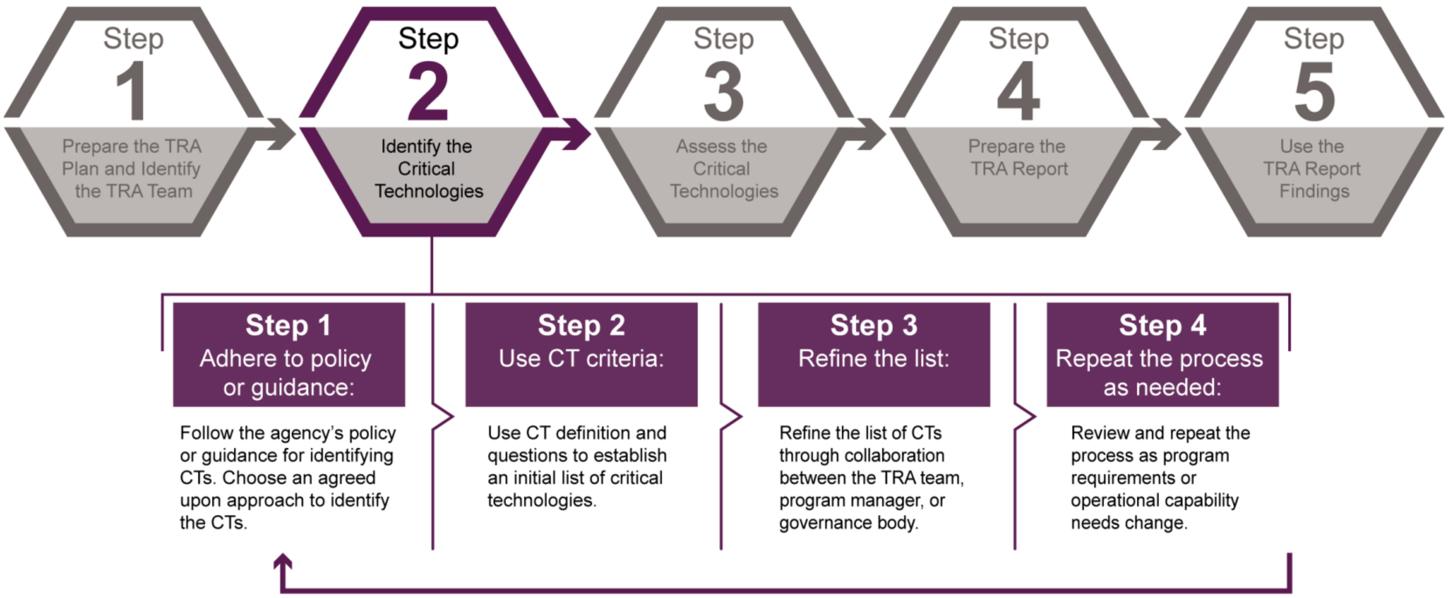
In 2015, the Navy conducted a TRA on the Columbia-class submarine program as part of its efforts to build 12 nuclear powered ballistic missile submarines for $126 billion. In using criteria from GAO's TRA Guide to evaluate the quality and completeness of the Navy's assessment of technology readiness and risk, GAO found that the Navy underrepresented the program's technology risks in its TRA when it did not identify several technologies as critical. We reported that the Navy did not follow our identified best practices for identifying critical technologies for the program, resulting in an underrepresentation of the technical risk. Development of critical technologies is key to meeting cost, schedule, and performance requirements. A high-quality TRA serves as the basis for realistic discussions on how to mitigate risks as programs move forward from the early stages of technology development. Not identifying these technologies as critical means Congress may not have had the full picture of the technology risks and their potential effect on cost, schedule, and performance goals as increasing financial commitments were made.

GAO, *Columbia Class Submarine: Immature Technologies Present Risks to Achieving Cost, Schedule, and Performance Goals*, GAO-18-158 (Washington, D.C.: December 21, 2017).

Four Steps for Selecting Critical Technologies

CTs should be rigorously identified and documented to ensure the TRA is credible, objective, reliable, and useful. The approach should be open and transparent to everyone in the process. This includes, but is not limited to, representatives from the research and development program office, the test community, and the science, engineering and user communities. Figure 5 depicts four steps that should help organizations identify and select their CTs. The steps can be scaled to projects of all sizes, from component technology development to large scale program acquisition.

Figure 5: Four Steps for Selecting Critical Technologies (CT)



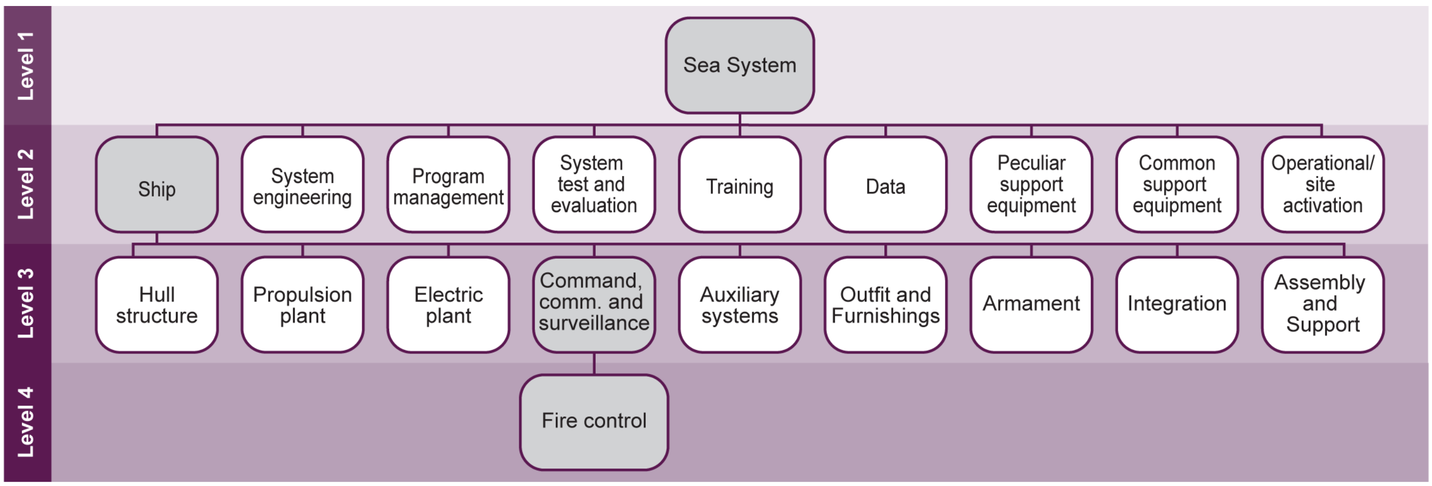
Source: GAO analysis and subject matter expert input. | GAO-20-48G

Step 1

The agency's policy or guidance establishes the approach for identifying CTs. In the absence of policy or guidance, the TRA team and program manager may reach an agreement on the approach to use. The most common approach that agencies and other organizations use is the work breakdown structure (WBS)—a deconstruction of a program's end product into smaller specific elements that are suitable for management control. It is the cornerstone of every program because it defines in detail the work necessary to accomplish a program's objectives. A WBS provides a consistent framework for planning and assigning responsibility for the work, and is an essential element for identifying activities in a program's integrated master schedule. The WBS is initially set up when a program is established and becomes successively detailed over time as more information becomes known about the program. Establishing a product-oriented WBS allows a program to track cost and schedule by defined deliverables, such as a hardware or software component.

The WBS 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 CTs. It can be used to identify CTs as well as low-risk heritage technologies.[34] Figure 6 shows a WBS with common elements for a sea system.

Figure 6: A Common Element Work Breakdown Structure (WBS)



Source: DOD. | GAO-20-48G

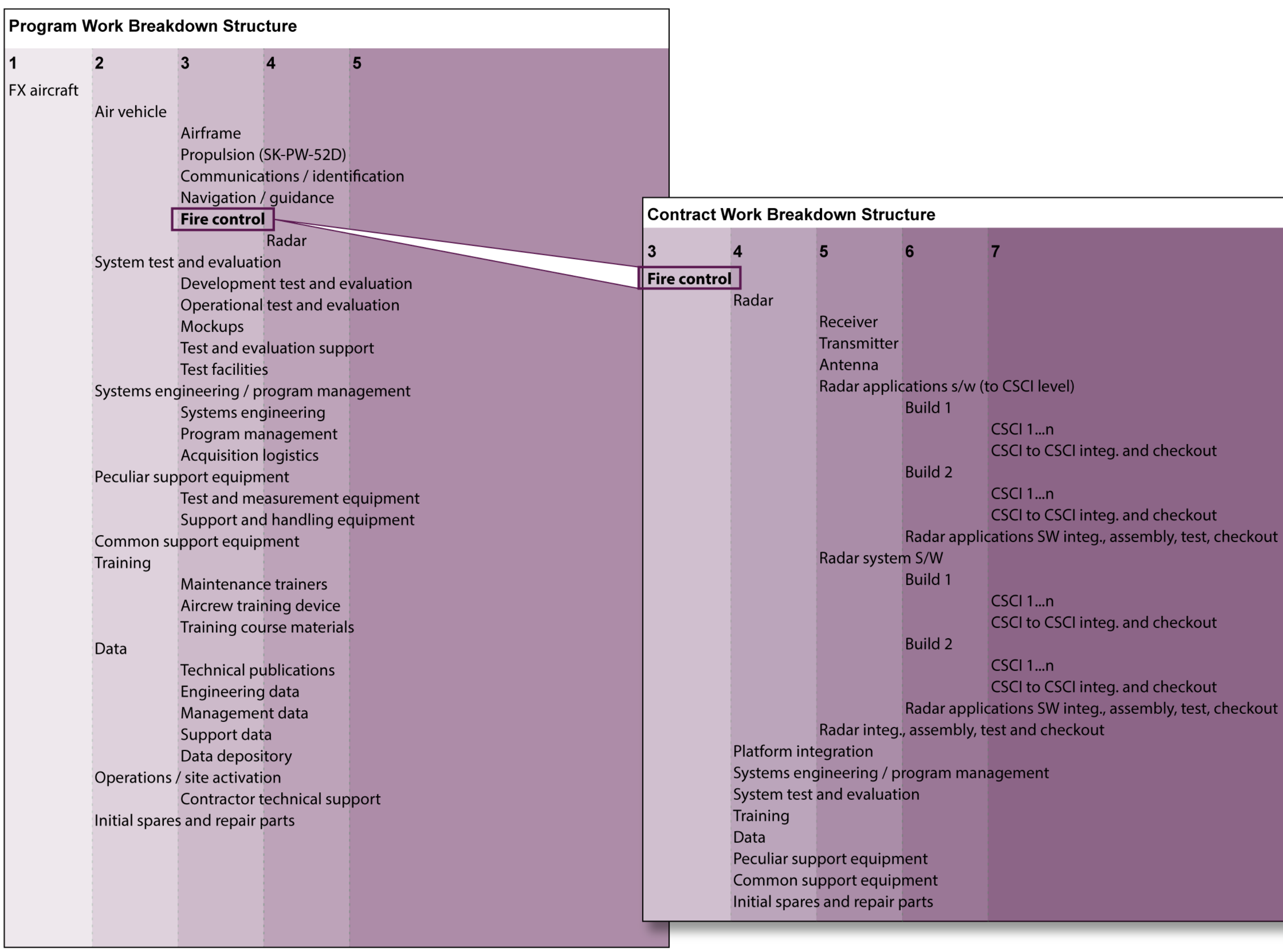
A well-defined WBS clearly delineates the logical relationship of all program elements and helps promote accountability by identifying work products that are independent of one another. Failing to include all work for all deliverables can lead to schedule delays and subsequent cost increases. It can also result in confusion among team members.

A well-developed WBS or equivalent supporting documentation is essential to the success of all acquisition programs. The WBS is typically developed and maintained by a systems engineering process 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 what work will be accomplished to satisfy a program's requirements. Elements such as hardware, software, and data are further broken down into specific lower-level elements. The lowest level of the WBS is defined as the work package level. By breaking work down into smaller elements, management can more easily plan and schedule the program's activities and assign responsibility for the work.

[34]Heritage technologies can become critical if they are being used in a new way where the form, fit, or function is changed; the environment to which it will be exposed in its new application is different than those for which it was originally qualified, or process changes have been made in its manufacture.

At the lower levels, a contractor or technology developer should 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 WBS' can identify all the technologies used by the system. Depending on the new or novel technologies that are needed for a system, CTs 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 (WBS)



Source: Department of Defense. | GAO-20-48G

Figure 7 shows how a prime contractor may require its subcontractor to use the WBS to report work progress. In this example, the fire control effort (a level 3 element in the prime contractor's WBS) is the first level for the subcontractor. Thus, all fire control elements at level 1 of the subcontractor's contract WBS would map to the fire control element at level 3 in the program WBS. This shows how a subcontractor would break a level 3 item down to lower levels to accomplish the work.

Similarly, a WBS for a project that has software elements should be broken down into specific lower level components as needed. Table 3 shows a WBS for a software project.

Table 3: 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: The Project Management Institute, Inc., Practice Standard for Work Breakdown Structures, 2d ed., © (2006). All rights reserved. Unauthorized reproduction of this material is strictly prohibited. | GAO-20-48G

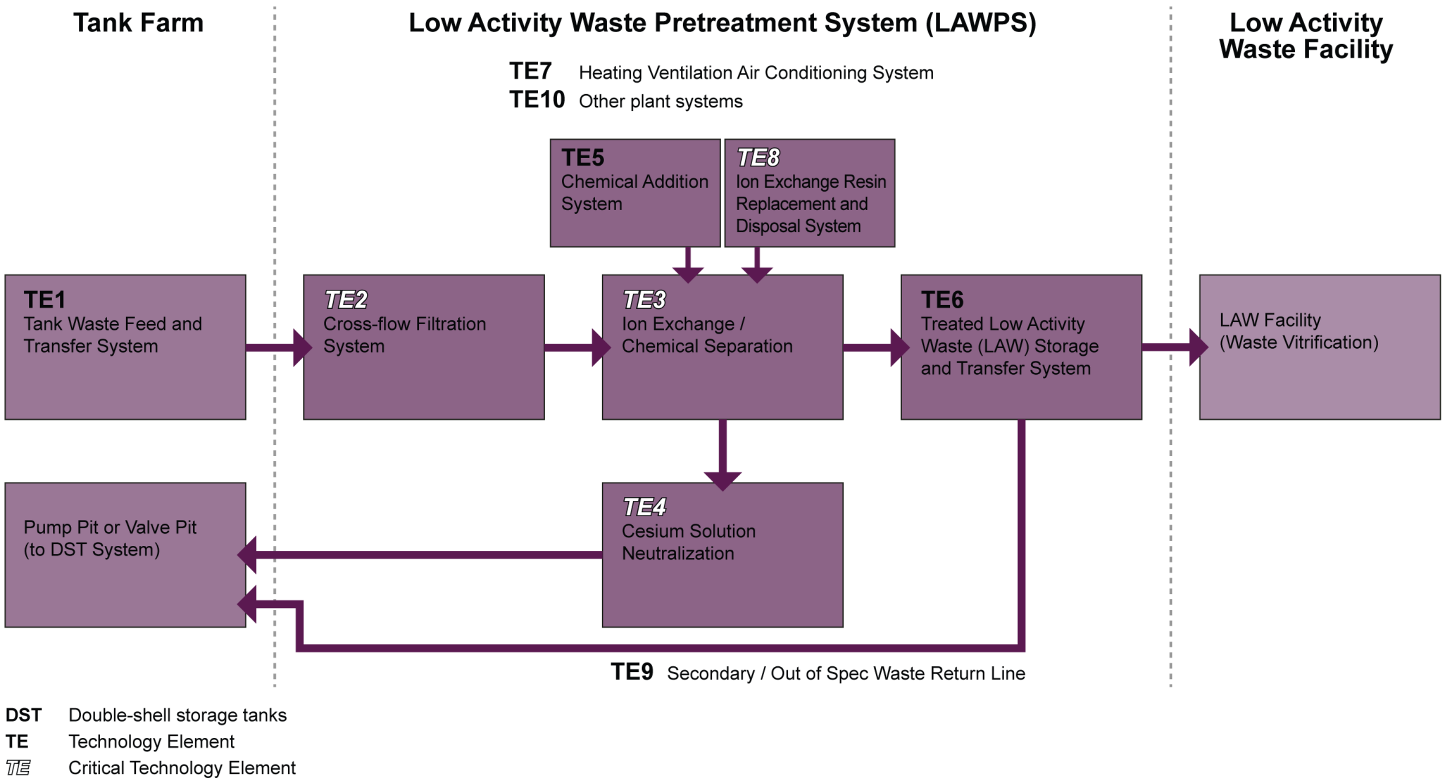
The use of WBS as a means of identifying CTs has several benefits, including:

- readily available;
- evolves with the system concept and design;
- represents all products or elements 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 relationships between the parts, the end product, and the tasks to be completed for each product in the system.

Using the WBS should be feasible for most programs, because it can be viewed 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 potential operating environments from documents, broad agency announcements, request for information, market surveys, actual results from government- or industry-funded efforts, program risk registers, and 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.

The nature of a project can also affect whether it is not possible to use a WBS to identify CTs. For example, DOE's Office of Environmental Management has determined that the WBS may not be all-inclusive for identifying CTs for its applications, so the office examines system flow sheets or diagrams (for example, those of chemical or nuclear waste processing facilities). 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 are CTs. Figure 8 shows a simplified flow sheet of 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-20-48G

Step 2

Technology elements are determined to be critical based on the CT definition (criteria) as specified in the organizations policy or guide, and cited in the TRA plan. In addition, criteria in the form of questions can be used to help in determining the initial list of CTs. The program manager or technology developer (or a designee) is generally responsible for identifying the initial list of CTs. This is accomplished by applying the CT definition and key questions coupled with the WBS, process flow diagram, or a similar approach.[35] Early identification of CTs may allow the program manager or technology developer to identify any additional areas of

[35]A process flow diagram is a diagram commonly used in chemical and process engineering to indicate the general flow of plant processes and equipment. The process flow diagram displays the relationship between major equipment of a plant facility and does not show minor details, such as piping details and designations.

technical expertise that are needed on the TRA team in order to fully evaluate the program.

We have compiled a list of questions from government agency TRA guides that can be used as a baseline in defining CTs and helping reconcile any disagreements between the team members, programmatic teams, or governance bodies. If the answer is “yes” to at least one question in each of the two lists, this signals the need to consider the technology for inclusion in the initial list of CTs.

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?[36]
- Could the technology have potential adverse interactions with systems with which it will interface?

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?

[36]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).

These questions are not comprehensive; they serve as a starting point for more in-depth questions that could be answered at different organizational levels. More detailed questions originate from the organization's knowledge base using engineering judgment or lessons learned and could be refined or tailored to match the program requirements. A best practice is for the TRA team and others, as appropriate, to confirm the list using more specific questions and requirements that pertain to the platform, program, or system in which they will operate.

Subject matter experts inside 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 CT candidate.

A best practice is to annotate the WBS and then list CTs with the reasons why other technologies were not selected. This allows anyone who participates in the TRA to see an account of how the CTs were systematically determined.

Step 3

The TRA team either affirms or refines the initial list of CTs. The TRA team may resolve any internal disagreements over the initial list of CTs and then should document the reasons behind the determination of each. If consensus cannot be reached, the TRA team leader makes the final determination, but alternate viewpoints should be documented and included in the final report.

In addition, the TRA team may critique the CT list or make its own list. If the TRA is being conducted for governance purposes, the list of CTs may be reviewed by members of the governance body, including acquisition executives, component heads, and agency senior leaders. CTs may be added to the list or removed, but these decisions should be transparent and documented. For knowledge-building TRAs, this process can be less formal but best practices should still be followed to the maximum extent possible.

Organizations should consider developing or tailoring guidance on how best to approach the determination (identification and selection) of CTs for their specific application, including communication across the organization with regard to decisions or activities that could affect how CTs 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 is for the TRA team to consider the intended operational environment in which they will operate when identifying CTs, and their interaction with other systems with which the technology being developed should interface. Technologies can be wrongly excluded as critical when programs have longstanding history, knowledge, or familiarity with them. By understanding the operational environment and interactions with other systems, CTs can be more easily identifiable. This consideration of interactions highlights whether the technology is being used in a new or novel way and whether it can have an adverse impact on the system. In addition, identifying the aspects of the intended operational environment that may be stressors or risks for the successful operation of a CT can help determine the relevant parts of the environment that should be the focus of earlier demonstrations and testing. The identification of CTs should be defined at a level that is testable, which could include the software needed to demonstrate their functionality.

Step 4

The program manager, TRA team, or governance body repeats the determination process, as needed. An early agreement should be reached on how changes to the list of CTs 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 engineers. During technology development and system development, it is likely that decisions could affect which technologies are considered critical.[37] These decisions may include changes to the system's proposed capabilities, its design, or its intended operational environment. In addition, alternative technologies may be selected as new technologies become available or if other technologies do not mature as expected. Thus, CTs may be added or removed from the list during the TRA process. These decisions should be documented and reviewed.

[37]This Guide refers to "technology development" as the design, development, and engineering of a critical technology or group of technologies, whereas "system development" refers to the design, engineering development, or product development of a system.

Identification of Other Important Technologies and Programmatic Issues

While selecting CTs is fundamental to the TRA, some technologies may not be characterized as a CT but are nevertheless important and could pose concern if certain conditions changed. For example, the TRA team may identify additional "watch items" that represent significant risk areas once system trades are final. Highlighting these watch items adds an additional level of visibility throughout the project.

While TRAs are not generally considered to be program assessments because the focus is on individual technologies, organizations have included areas beyond CTs as part of their internal TRA guides and processes. For example, the Air Force considers programmatic issues important to evaluations because these can affect technology development. The Air Force includes program issues in its TRL calculator, a tool for identifying, evaluating, and tracking CTs.[38] DOE has also developed standard TRL calculators that include programmatic aspects.[39]

A best practices checklist that includes the corresponding high-quality characteristics related to identifying the CTs is included below.

Best Practice Checklist: Identifying the Critical Technologies

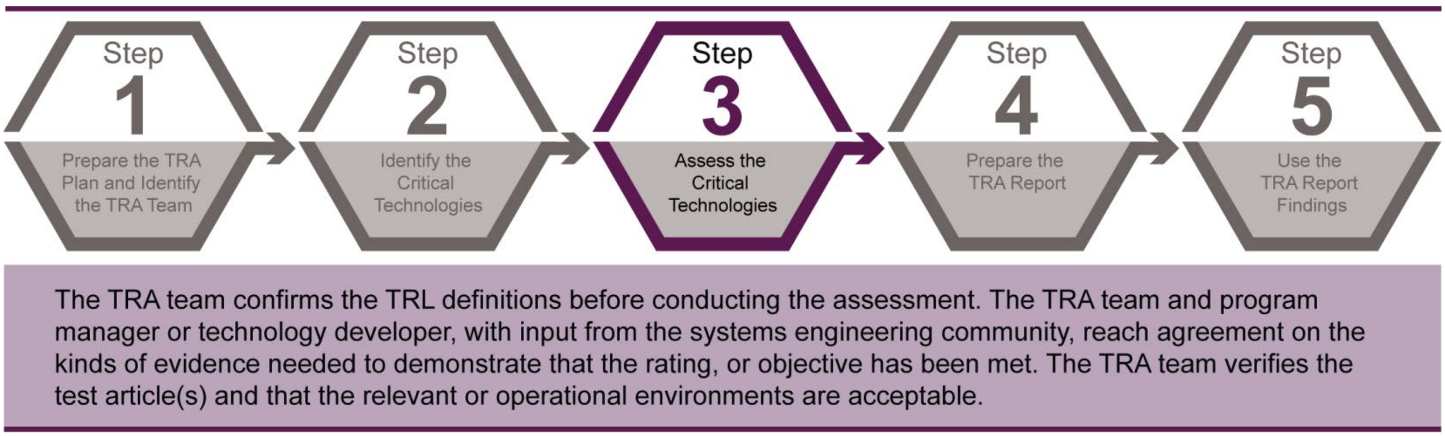
- CTs are selected by following a reliable, disciplined, and repeatable process. (Reliable)
- CTs are selected based on consideration of the newness or novelty of technologies and how they plan to be used (Credible)
- CTs are selected based on consideration of the operational performance requirements and its potential to affect cost and schedule outcomes. (Credible)

[38]Some experts familiar with the tool assert that the calculator is useful in applying the TRL concept to research and development programs. They report that the calculator simplifies determining the appropriate TRL for a given technology. By presenting a standard set of questions to users, the calculator makes the process repeatable. The standard format facilitates the comparison of different technologies and can accommodate both hardware and software development projects. Other experts do not agree with the use of calculators because of concerns associated with box-checking where critical evaluation could be compromised.

[39]DOE has developed standard TRL calculators that not only address technical maturity, but also include 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 (e.g., 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.

- A relevant environment is derived for each CT from those aspects of the operational environment determined to be a risk for the successful operation of that technology. (Credible)
- The potential adverse interaction with systems which the technology being developed should interface is considered as part of the determination of CTs. (Credible)
- The selection of CTs is confirmed, using more specific questions and requirements that pertain to the platform, program, or system in which they will operate, is confirmed by the TRA team and others, as appropriate. (Objective)
- The number of CTs selected for the assessment is not arbitrary and is based on solid analysis using the WBS, technical baseline description, process flow diagrams, or other key program documents. (Objective)
- CTs are selected during early development. (Credible)
- CTs are defined at a testable level, including any software needed to demonstrate their functionality. (Credible)
- The TRA team documents the reasons why technologies are selected as critical, including reasons why other technologies are not selected as critical. (Reliable)

Step 3 – Assess the Critical Technologies



Source: GAO. | GAO-20-48G

To determine the maturity of CTs, the TRA team assesses them and determines a TRL for each one.[40] The TRLs are determined through an objective evaluation of information against general criteria. These criteria are defined in the TRL descriptions and are confirmed by the program manager, technology developer, and TRA team lead.

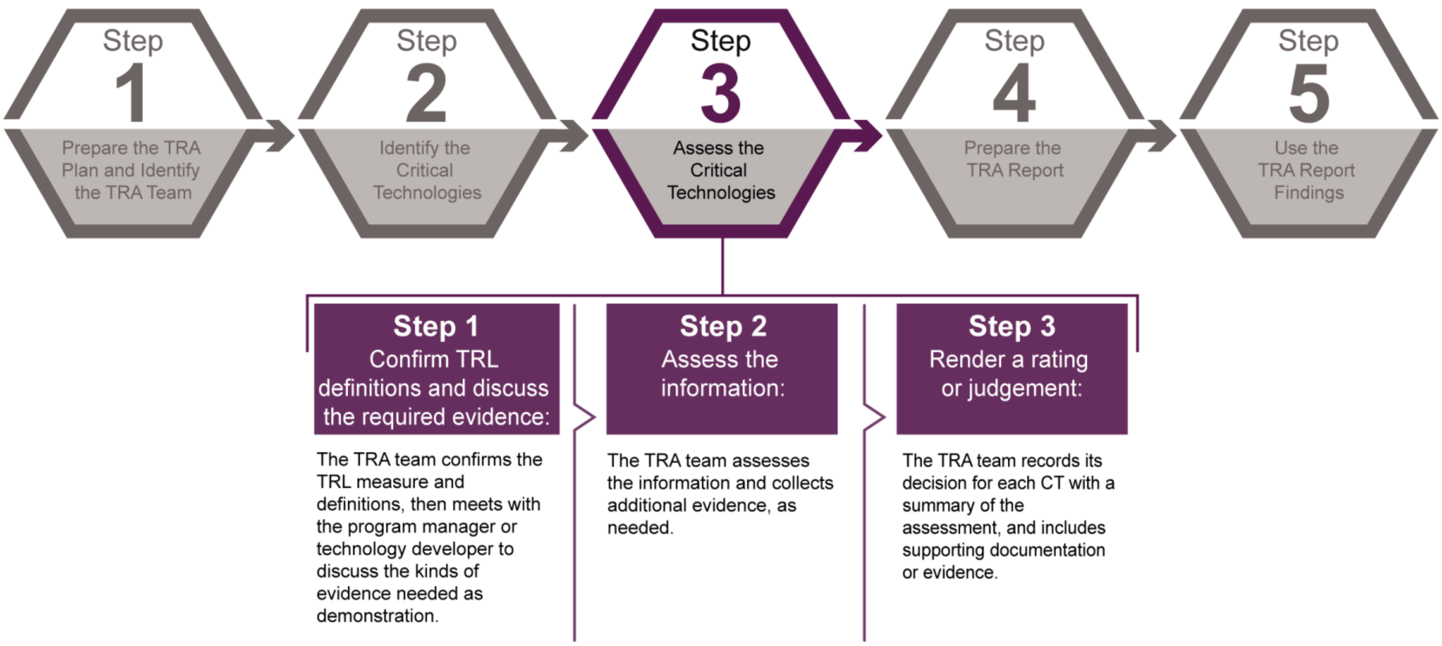
To conduct a high-quality assessment of CTs, the TRA team needs access to all the relevant information. Such information may include schematics, test data, and analytical reports, among other key information. Depending on whether the TRA team is to certify the readiness of CTs for a governance body at a decision point or assess the maturation of technologies as a knowledge-building exercise, both the program manager and the TRA lead should understand why the assessment is being conducted, what constitutes sufficient evidence that a specified TRL has been achieved, and within what operational environment the technology is expected to operate.

[40]Conducting an independent assessment of CT’s is crucial to establishing confidence in the TRA. The independent TRA team should verify, modify, and correct an assessment as necessary to ensure realism, completeness, and consistency.

Three Steps for Evaluating Critical Technologies

Evaluating CTs is the primary purpose of the TRA. Figure 9 depicts three steps that can help organizations ensure that an evaluation is objective and reliable by applying a disciplined and repeatable process. In some cases, the steps can be tailored to accommodate organizational structures, processes, and policies.

Figure 9: Three Steps to Evaluate Critical Technologies (CT)



Source: GAO analysis and subject matter expert input. | GAO-20-48G

Step 1

The TRA team confirms whether the TRL measures and definitions selected during the development of the TRA plan are still appropriate. The TRA team meets with the program manager or technology developer, with input from the systems engineering community, to discuss the kinds of evidence that are sufficient to demonstrate that a CT has achieved a specific TRL, or other stated goal. A best practice is that the TRA team should interview the test officials and verify that the test article and the relevant or operational environment used for testing are acceptable.

Step 2

The TRA team conducts the assessment and reviews the information (evidence). 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 TRA team can objectively evaluate the CT in proper context. If necessary, additional information is obtained from the program manager and technology developer in order to evaluate the CTs and assign a TRL or determine whether a goal has been met. When possible, the TRA team should consider any analogous system technology assessments to aid their review. Additionally, in cases where synergy can be gained by examining similar or related systems, relevant and operational environments, and concepts of operations, the TRA team should take full advantage of applicable technology maturity artifacts. Once the TRA team considers the information and reaches a consensus, it generally chooses one of the following options:

- Option 1 - The TRA 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 assessment is needed.[41]
- Option 2 - If the TRA team determines that information is insufficient to render a credible, objective, and reliable decision, the team asks the program manager for more information to make a TRL rating determination for each CT. The interaction between the TRA team and program manager is often an iterative process as discussions can highlight the need for more information, or raise additional questions.
- Option 3 - The TRA team may determine that a TRL rating cannot be assigned because the fidelity of the test article or test environment is insufficient and 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 should be done to conduct a TRA.

Programs should establish channels of communication across the organization so that decisions or activities that can affect whether the CTs being evaluated may need to be reconsidered or reassessed. The most common pitfall among organizations is that changes are not coordinated

[41]The TRA team defines the appropriate (or acceptable) test environments, which may differ from those that the program manager selects. The test environment should reflect what was determined to be the appropriate relevant environment for the technology being tested. 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 requiring not too much data (system not too expensive) to prove acceptability.

or communicated with others, particularly when technology development or system development occurs in parallel under different organizations. Gaps in communications can be costly and result in unnecessary schedule delays.

Step 3

The TRA team summarizes the TRL rating of each CT, including supporting documentation, to justify the assigned TRL. Table 4 lists one generic list of supporting information that can be extracted or referenced to support a TRL rating. Because the definitions are not all inclusive and can vary by technology and application, organizations can tailor the definitions to accommodate their own application. Other TRL definitions can be found in appendix IV.

Table 4: Technology Readiness Levels (TRLs) and the Information Needed to Demonstrate Them for Hardware and Software

		Supporting information needed	
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
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

		Supporting information needed	
TRL	**Definition**	**Hardware**	**Software**
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: GAO presentation of Department of Defense information. | GAO-20-48G

High-quality TRAs rely upon artifacts and information, such as requirement documents, analyses, test reports, and environmental test results. The availability of such information can depend on the acquisition phase of the CT, technology application, and level of complexity of the technology. These can range from simple technologies with just a few drawings to very technical analytical reports on nuclear waste facilities, space systems, defense weapon systems, or highly distributed information technology business systems.

The program manager and the TRA team use this information and the summaries as support when writing the TRA report. If the TRA team and program manager cannot reach consensus on a TRL rating, the dissenting views should be presented in the TRA report and accompanied by evidence that supports both sides (see the chapter titled *Step 4 -*

Prepare the TRA Report for information on how dissenting views should be addressed and documented).

Documenting Test Results and the Operational Environment for Assessments

As technologies mature, TRAs are conducted to determine whether the supporting information can demonstrate the state of progress and whether it has reached a certain TRL goal or expectation. CT performance should ultimately be demonstrated in an operational environment before it is considered mature enough to begin integration into the system, typically at TRL 7. In some special cases, such as the space environment, it would be impractical to test a technology in its operational environment, so TRL 6 can be acceptable.

The TRA team conducting the assessment documents the state of the CT (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 TRA team may have examined the article or interviewed test officials to verify that these are acceptable artifacts. The test environment should be described in sufficient detail that the TRA 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 are required to achieve statistical significance. In addition, testing and performance verification may be augmented with calibrated models and simulations.

When and where applicable, other supporting information to be recorded includes:

- identification of test agencies;
- when and where tests are performed;
- the cause of problems encountered, their solutions, and resulting changes in the test plan; and
- unresolved issues discovered in testing and the plans, options, or actions required before moving further in development.

For CTs related specifically to information technology, the environment includes physical, logical, data, and security environments, such as:

- the physical environment includes mechanical components, processors, servers, and electronics; thermal and heat transfer; electrical and electromagnetic; threat (e.g., jammers); climatic—weather, temperature, particulate; network infrastructure;
- the logical environment includes other applications, run-time (e.g., operating system, and middleware), security interfaces, web enablement, layers of abstraction, communication protocols, and backward compatibility;
- the data environment includes formats, structures, models, schemas, data rates, latency, and data packaging and framing; and
- the security environment includes firewalls, appliqués, nature of the cyber adversary, methods of attack, trust establishment, and security domains.

Creating Critical Technology Subsets for Exceptionally Large or Complex Programs

CTs need to be selected and named for the technologies themselves, not the functionality or other nontechnology approaches. Since a TRL rating reflects the status of the technology being evaluated, the focus should remain on that selection. For programs with an unwieldy number of CTs, especially programs like systems of systems, it may be beneficial to group 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 100 CTs, similar critical technologies could be grouped into several subsets of 10-12 CTs. Specifically, the F-35 program office (formerly called Joint Strike Fighter) identified CT areas encompassing avionics, flight systems, manufacturing and producibility, propulsion, supportability, and weapons delivery system, all of which were made up of many components. It is important to note that the TRL is determined by the lowest TRL of CTs within a group, and is not an average of all the TRLs in a subset or larger group set.

Using TRL Calculators

The use of TRL calculators as a tool to assess CT's has drawn mixed views. Some experts familiar with calculators assert that they are useful in applying the TRL concept to research and development projects. These proponents report that the calculator simplifies determining the appropriate TRL for a given CT. By presenting a standard set of questions to users, the calculator makes the process repeatable. The standard format facilitates the comparison of different technologies and can accommodate both hardware and software development programs. Other experts do not support the use of calculators because they might facilitate box-checking, which could compromise critical judgements.

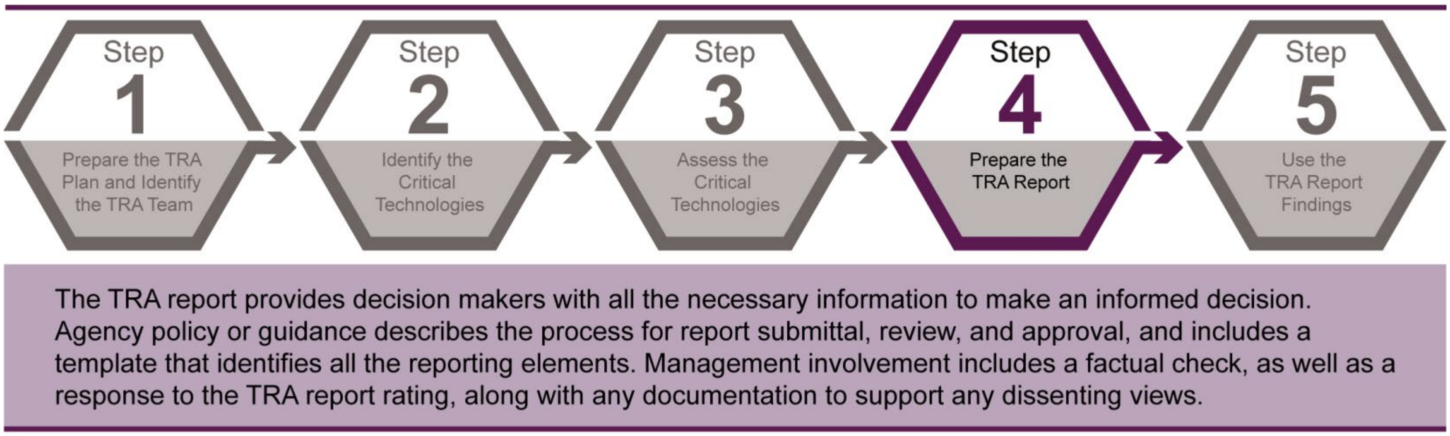
At DOE, a standard TRL calculator is used to evaluate technical maturity, but is also used on programmatic and manufacturability aspects, associated with the critical technology elements. Additionally, due to the general types of application of the TRA process within the DOE Office of Environmental Management (e. g., radioactive chemical waste processing systems), the organization includes TRL calculators that assess the maturity of the integrated processing system at critical decision points in the project.

A best practices checklist that includes the corresponding high-quality characteristics related to evaluating the CTs is included below.

Best Practice Checklist: Evaluating the Critical Technologies

- The TRA team confirms the TRL measure and definitions selected during the planning phase is still appropriate, and reaches agreement with the program manager on kinds of evidence needed to demonstrate that a TRA goal or objective has been met. (Reliable)
- The TRA team interviews the testing officials and verifies that the test article and the relevant or operational environment used for testing are acceptable and that the results are sufficient. (Objective)
- The TRA team assigns a TRL rating for each CT based on credible and verified evidence, such as test and analytical reports, requirements documents, schematics, and other key documents. (Objective)

Step 4 – Prepare the TRA Report



Source: GAO. | GAO-20-48G

TRA reports provide useful information about the maturity of technology, its state of development, and the potential areas of concern and risk. The information can put decision makers in a better position to identify maturity gaps, formulate plans for maturing technologies, address potential concerns, and determine whether programs that will integrate CTs have achieved TRLs at a certain decision point and are ready to move to the next acquisition phase.

Agencies should have policy or guidance on how TRA reports should be prepared, including the processes and steps to create the report; reporting elements; process for submittal, review and approval, how the results are communicated, and who is involved in the process. For auditors, these processes and the TRA report provide sufficient evidence of the practices used to conduct high-quality TRAs. Because stakeholders review TRA reports with different perspectives and goals, the information should be presented clearly and logically.

The TRA Report

The content in a TRA report can vary based on its purpose. TRA reports for governance purposes are developed to certify whether CTs have met an expected TRL rating and governing authorities use them to determine whether a program is ready to move to the next acquisition phase. Knowledge-building TRA reports prepared for program managers and technology developers are conducted with a focus on maturing technologies, not as a pass/fail assessment. Therefore, the information collected is to be used as a source of information for managing those efforts. For example, knowledge-building TRA reports can be used to learn about specific aspects of technology or prototype development, such as identify gaps in maturity or areas that may be challenging, or gather evidence to continue development efforts or initiate steps toward using an alternative or backup technology, or determine whether CTs are ready for a TRA for governance bodies at an upcoming decision point.

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

Figure 10: Technology Readiness Assessment (TRA) Report Template

TRA 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) rating determination made by the TRA team for each.

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.
- Test Results: describe the analytical reports, test reports, or other information that was used to test the readiness, and functionality of the critical technology.

EXECUTIVE APPROVAL

- Provide statement or memo that shows executive management review and approval of the TRA report.

ATTACHMENTS

Include the following planning documents:

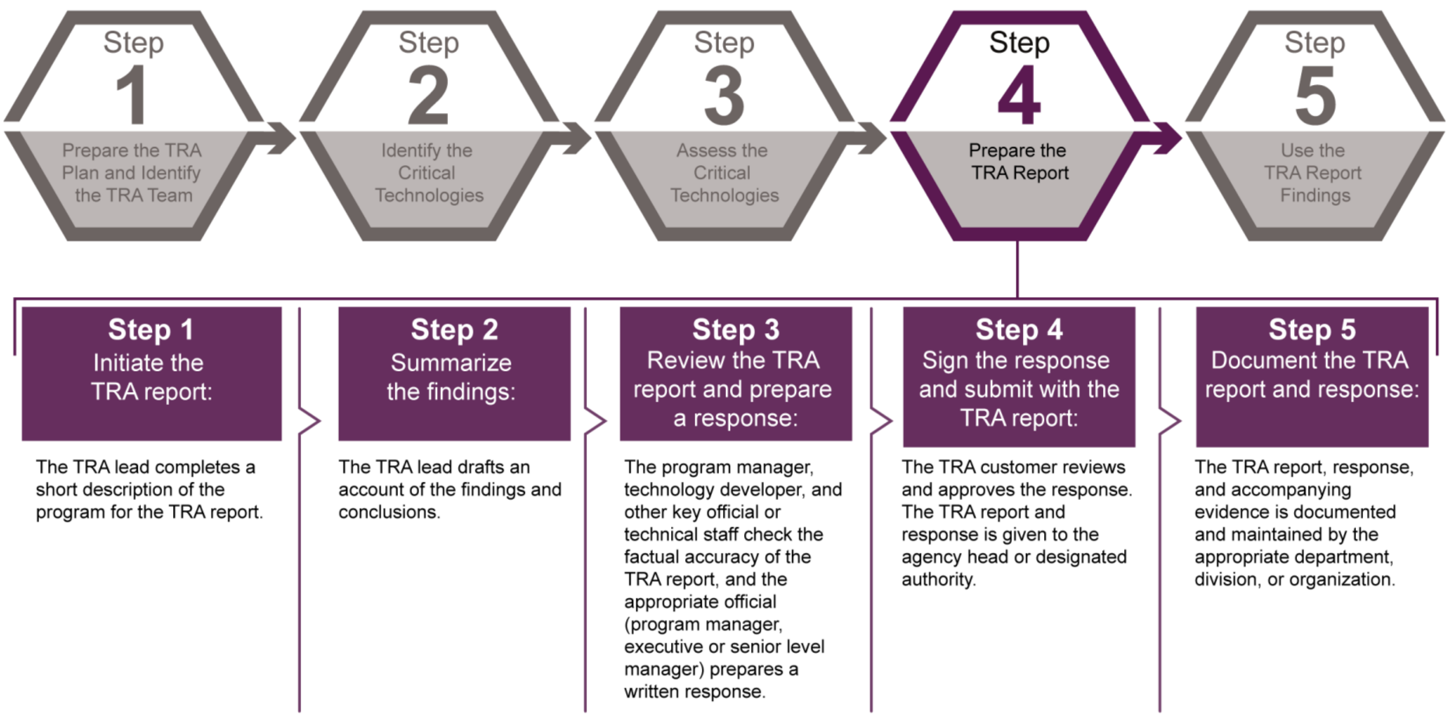
- TRA Plan
- Supporting documentation for identification of critical technologies
- Completed tables: TRL Questions for critical technologies
- List of support documentation for TRL determination
- TRL Summary table
- Lessons Learned
- Team biographies

Source: GAO analysis of agency documents. | GAO-20-48G

Five Steps for Preparing and Submitting the TRA Report

The TRA team lead prepares and coordinates the TRA report, with detailed input from members of the TRA team, before submitting it to the appropriate organizational officials. Figure 11 shows five generic steps to prepare, coordinate, approve, and document the TRA report.

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



Source: GAO analysis and subject matter expert input. | GAO-20-48G

Step 1

The TRA report draft is initiated. For this step, the TRA team lead documents the introduction and other descriptive information in the TRA report. The TRA report summary should explain the function of each CT at the component, system, and subsystem levels. The TRA report should also explicitly describe the program increments or spiral developments.[42]

Step 2

The TRA team lead 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.[43] 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.[44] In addition, the report should document any additional changes to the critical technology list made during the CT assessment phase.

Step 3

The program manager, technology developer, and other key officials or technical staff check the factual accuracy of the TRA report, and the appropriate official (program manager, executive or senior level manager) prepares a written response. This response may be a cover letter, memorandum, or other 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

[42]A program increment or spiral development refers to the specific version of the CTs being assessed. CTs 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.

[43]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 TRA team should be prepared to list and summarize them in the TRA report, as appropriate.

[44]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.

nonconcurrence with the TRA team's rating of the CTs.[45] The purpose of the written response is to document the coordination among the various stakeholders and organizations, and agreement or dissenting viewpoints with the TRA team's findings, along with supporting analyses for any disagreements. The science and technology executive should certify that he/she stands behind the results or provide rationale for any dissenting views or differences of opinion. The acquisition executive or appropriate official approves the response and forwards it to the organizational or agency head.[46] If factual accuracies have been compromised—due to new information, misinterpretation of data, etc.—the TRA report is revised with concurrence of the TRA team to correct any inaccuracies.[47] An accompanying log should keep an account of how each issue was addressed and resolved.[48] 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 factually correct.

Step 4

The TRA customer reviews and approves (signs) the response. The TRA report along with the response is forwarded to the agency head or designated authority, the organization's convening independent review board, or the governance body. This step is not included for knowledge-building TRA reports that are specifically prepared for program managers and technology developers where the information is strictly used for internal management purposes.

[45]The science and technology executive is identified because the official generally has oversight of technology projects entering development early in the acquisition or project life-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.

[46]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.

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

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

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 CTs 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 to allow decision makers sufficient time for their 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 rating 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 TRA team should reference relevant portions of the project's technical assessment reports when developing the TRA report.

Appendix VI provides websites where TRA report examples can be found.

Final Processing of the TRA Report

The program manager or other official should prepare a written response (via cover letter and memorandum) to indicate agreement or a dissenting viewpoint with the TRA rating of the CTs. The written response is attached to the TRA report and is coordinated and signed by the appropriate senior officials, such as the project manager, science and technology executive, acquisition executive, or other organizational head. The written response may include other relevant technical information to support an opposing view. A formal response is not required if the report is prepared as a knowledge-building TRA, where the information is to be used for internal purposes only. Organizations may employ similar strategies so that differences of opinion can be discussed to reach consensus on the TRA report findings.

Dissenting Views

Dissenting views can occur when the project manager, science and technology executive, or other official disagrees with the TRA team's conclusions.[49] Such differences of opinion are formally documented as a memorandum and should be included as an attachment to the TRA report. Any major disagreement with the TRA team's findings should be brief and succinctly explained in the written response in a clear, logical, and rational way. In addition, dissenting views should be supported by sufficient evidence, such as analyses, test documents, and other technical information. In other words, the dissenting view should be evidence-based, and well supported by a reliable body of evidence.

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 a similar approach so that differences of opinion can be discussed to reach consensus on the assessment findings. While TRAs conducted for knowledge-building purposes do not require external oversight by governance bodies, it is essential that organizations perform the necessary steps and activities to ensure that the findings are objective and useful.

Next Steps after Completion of the TRA Report

After completion of the TRA report, organizations should provide the information to others who may use them in other key planning and analytical documents, such as the TMP, risk management plans, and cost and schedule assessments. In this Guide, we discuss the TMP in the next chapter as a separate and distinct activity. However, some organizations, such as DOE and the National Security Agency, include the TMP as part of the TRA report.

A best practices checklist that includes the corresponding high-quality characteristics related to preparing the TRA report is included below.

Best Practice Checklist: Preparing the TRA Report

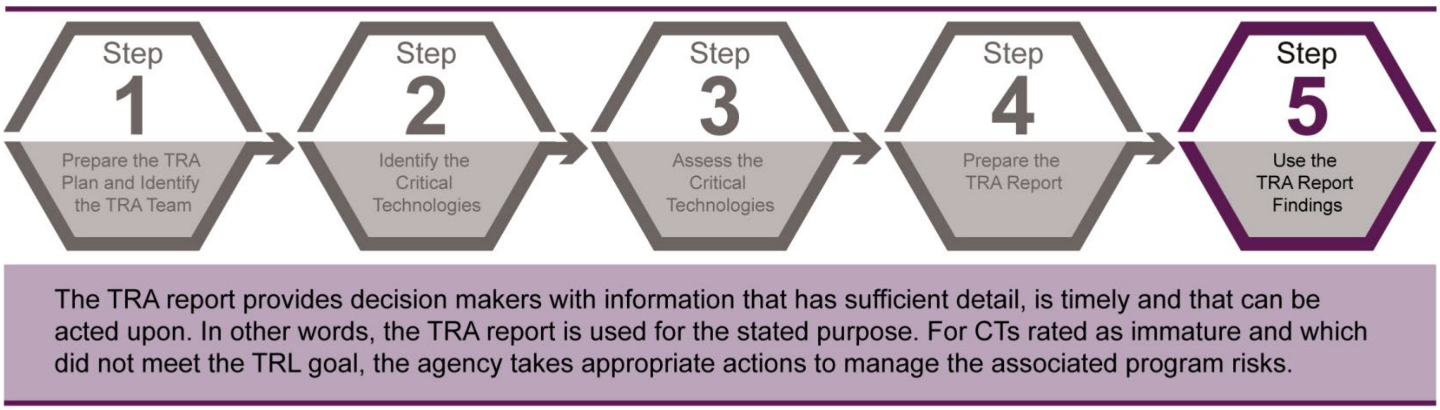
- Policy or guidance details how TRA reports should be prepared, including a template that identifies the elements to report, process for submission, review and approval, how the report should be communicated, and who should be involved. (Reliable)
- The TRA report includes all the key information: (Reliable):

[49]At many organizations, the science and technology executive has oversight of technology projects during the early technology development acquisition phase. 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.

- executive summary
- program background
- purpose and scope of the TRA
- description of the process for conducting the TRA, including the selection of CTs
- rating for each CT assessed
- supporting evidence for each CT assessed, including references to test results and other key documents
- executive approval of the results

- Upon completion of the assessment by the TRA team, management checks or attests the factual accuracy of the TRA report. (Objective)
- The TRA report includes management's written response to the TRL rating (i.e., concurrence, or dissenting views in a memorandum or cover sheet). For example, if the program manager does not agree with the TRA team's assessment, then the reason for the dissenting view should be clearly written, logical, rational, and supported by evidence. (Reliable)

Step 5 – Use the TRA Report Findings



Source: GAO. | GAO-20-48G

The TRA report is used to inform governance bodies, program managers, and technology developers about the readiness of CTs, in order to help them make an assortment of decisions. These decisions can range from those made by governance bodies to determine if programs that depend on CTs are ready to move forward, to those made by program managers and technology developers for knowledge-building TRAs who use them in their day-to-day responsibilities to mature technologies or to consider tradeoffs in light of changes in cost, schedule or program priorities. In addition, systems engineers may use TRA reports to better understand the transition risks when maturing technologies, or to determine whether technologies are ready to transition to new or existing acquisition programs.

It is important to point out that each organization involved in the development and maturation of CTs has its own culture, perspective, or bias that can influence how a TRA report is interpreted. These viewpoints can influence how the TRA report may be understood or acted upon. Anecdotal reports suggest that program managers and technology developers have influenced the TRA rating because of other program goals, such as budget or schedule pressures, or other expectations. Because program managers are rated on their ability to deliver projects within certain budget, schedule, or technical expectations, they are at increased risk of making unnecessary compromises. For this reason, organizations should be vigilant in viewing the TRA reports with professional judgment.

A best practice is that the TRA report should be used for its stated purpose, such as to inform decision makers about whether a prescribed TRL goal has been met or identify potential areas of concern or risk. TRA reports should provide useful information so that decision makers can rely on them to identify technology maturity gaps, decide when and how technology development efforts should move forward, consider whether backup or alternative technology solutions should be considered, and obtain information as a source of input for other analyses, such as updating a program risk management plan, or revising cost and schedule risk assessments.

The TRA report can also:

- inform the integrated project team in preparing technology maturation plans to achieve an acceptable maturity roadmap for CTs prior to a decision point or stage gate;
- provide a basis for modifying the requirements if technological risks are too high;
- help 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;
- help 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; and
- augment knowledge building and continuous improvement as an important part of an evolving TRA process and identify lessons learned that benefit future TRAs and/or technology development projects that should be identified during the TRA process.

TRAs are point-in-time evaluations and this should be taken into account by decision makers when using their results. That is, TRAs are snapshots of how a CT has been demonstrated at 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.

A best practice is to document lessons learned within the TRA report or 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.

TRAs for Governance Decisions

At decision points or stage gates, governance bodies use TRA reports to evaluate or certify that CTs have reached a prescribed TRL. 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 information to decide whether CTs are sufficiently mature and the program or project that will integrate them is ready to move to the next acquisition phase. Governance bodies review the TRA report most commonly before the decision to start system development—the point when program requirements should be matched to organizational resources—but can also use them at other decision points depending on the cost, schedule, or technical risk that may warrant their use.[50] At DOD, the MDA is the governing official who certifies 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.[51] GAO recommends that CTs reach TRL 7 at the decision point to start system development. In some special cases, such as the space environment, it would be impractical to test a technology in its operational environment, so TRL 6 can be acceptable. At DOE, the governing official reviews the TRA results prior to critical decision (CD) 2—at TRL 6 where

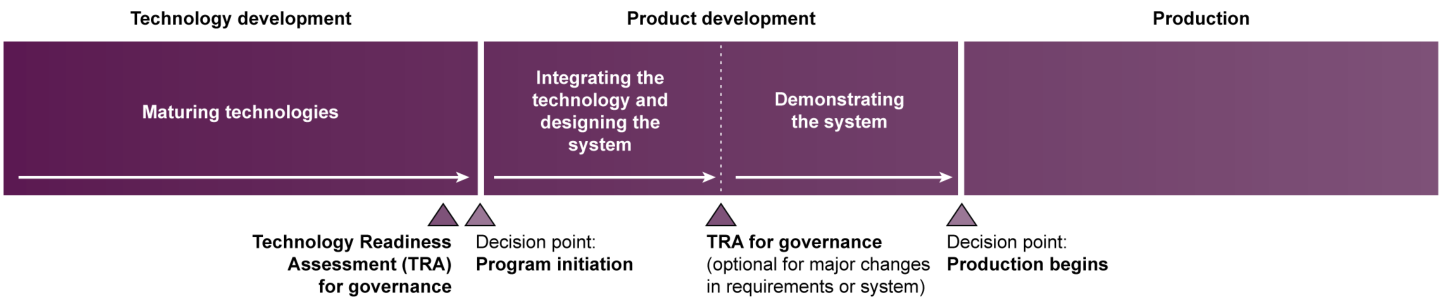
[50]A TRA is not a pass/fail exercise and is not intended to provide a value judgment of the technology developers, technology development program, or program/project office. It is a review process to ensure that CTs reflected in a project design have been demonstrated to work as intended (technology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

[51]10 U.S.C. § 2366b. The law allows the MDA to waive certification and determination 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 determination, and the reasons for the waiver determination have to be submitted in writing to the Congressional defense committees within 30 days of waiver authorization. The MDA for an MDAP reaching Milestone A after October 1, 2016, is the Service Acquisition Executive (SAE) of the Military Department that is managing the program, unless another official is designated to serve as the MDA. *See,* FY16 NDAA, Pub. L. No.114-92, Sec. 825(a)-(c)(2), 129 Stat. 726, 908 (Nov. 25, 2015) ; DoDI 5000.02, Chg. 3, para 4; and DoD (DCMO) Memorandum, Guidance on Department of Defense Implementation of Section 2430(d) of Title 10, United States Code, of December 18, 2017.

approval for the project baseline occurs.[52] At NASA, in recent years, most major projects in development reported that they matured their technologies to TRL 6 by preliminary design review.

Figure 12 shows a simplified acquisition or project life-cycle with notional decision points to highlight where TRAs may be conducted to govern programs. Each organization should determine when and how often TRAs for such purposes should be conducted to accommodate its own requirements, technology considerations, and risk tolerance.

Figure 12: Acquisition or Project Life-cycle with Technology Readiness Assessments (TRA) at Decision Points for Governance



Source: GAO analysis of agency documents and subject matter expert input. | GAO-20-48G

Knowledge-Building TRA Reports for Project Management

Knowledge-building TRA reports are used by technology developers or program managers in their day-to-day responsibilities for maturing CTs, systems, or sub-systems. These reports are prepared in the interim periods between decision points, beginning from the early technology development phase—typically where analytical and experimental critical function or characteristic proof of concept occurs at TRL 3—through the completion of the system and its qualified test and demonstration at TRL 8. While formal TRA reports are used at key decision points, knowledge-building TRA reports are used as project self-assessments to make a

[52]According to DOE officials, in the next iteration of their guidance, if the total project cost for a DOE application exceeds $750 million, 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 of 6 at CD-2, and projects are encouraged to achieve TRL 7 prior to CD-3 as a recognized best practice.

broad range of decisions.[53] These include (1) learning about specific aspects of technology development efforts, such as calculating progress in achieving technical performance goals for a specific technology or group of technologies; (2) gathering evidence either to continue development efforts or to initiate steps toward using an alternative or backup technology; (3) demonstrating the performance of fieldable technologies or prototypes; (4) making decisions about transitioning technologies to new or existing acquisition programs; or (5) deciding whether CTs are ready for TRAs for governance bodies at a decision point.[54]

TRAs and Risk Reduction Efforts

TRA reports are used to illuminate potential areas of concern or risk. They facilitate discussions between the program manager and customers on how to mitigate potential risks at the various phases of development. When done before the program initiation phase, TRA reports can complement the pursuit of risk reduction efforts to ensure technologies are adequately mature by the time they reach key decision points. Knowledge-building TRAs may be conducted during the technology development phase to support developmental efforts, including risk reduction efforts. For example, technology developers and program managers may use information gathered via knowledge-building TRAs to determine whether technologies are ready to undergo an official TRA for governance purposes. Organizations should not ignore or dismiss the risks discovered as part of the TRA or proceed with optimism without addressing maturity concerns.

[53]Self-assessments or peer reviews are used in some agencies to accomplish interim assessments. 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.

[54]The TRA report and other analyses 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.

TRA reports themselves do not eliminate technology risk, nor do they preclude taking risks. But they do alert decision makers and other stakeholders who are interested to potential areas that could be problematic and inform future actions. The TRA report should clearly state the TRL rating for each CT, at a minimum, and include the basis for the decisions made. Decision makers can use this information to identify gaps between the expected TRL and the actual TRL. Aware of potential concerns, organizations may further investigate and analyze any concerns raised in order to better understand the potential risks, challenges to development, and potential cost and schedule implications.

Options for Addressing Immature Critical Technologies

When certain CTs are assessed as immature or as not progressing as planned, a best practice is to use the TRA report information as basis to:

- consider or identify an alternate or backup technology;
- initiate development of a TMP, a project management tool that is used to address immature CTs (see the next chapter in this guide for more information on this tool);[55]
- update the program's risk management plan by ensuring that all potential CTs are included in the program's risk management database and plan; and
- update or revise cost and schedule risk assessments, as appropriate.

It is important for program managers and technology developers to understand that CTs rated at a lower TRL than expected necessitate the development of a plan for maturing these technologies, among other options. What is unacceptable is to discover immaturity and then proceed with the assumption that maturity of the CT will just happen as planned and as scheduled.

As decision makers use the TRA report to plan how technology development efforts should proceed, maturing the CT from one level to the next may take varying amounts of effort, depending on the CT and the readiness level. Indeed, the amount of time, effort, and activities needed to advance the technology to a higher TRL may not only differ largely between TRLs but also may not increase linearly between progressively

[55]Organizations employ similar methods to mitigate technology risks as part of their own systems engineering or program management processes, such as those used by 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.

higher TRLs. 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. While TRAs may determine the maturity of a technology, they do not in and of themselves inform the technology developer or program manager of what is required to successfully complete its development.

Relationship between TRA Reports and Other Project Management Tools

Organizations may combine the TRA report with other project management tools to help them better understand risk and decide how to effectively manage and develop CTs. For example, DOD employs 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 5 lists some of the more commonly known project management tools that can be used in combination with TRAs.

Table 5: Examples of Program Management Tools and Analytical Approaches 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 with risk information in the form of 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. (https://apps.dtic.mil/dtic/tr/fulltext/u2/a507591.pdf)
Risk assessment matrix	A process used for understanding the nature, sources, and causes of identified risks for estimating risk levels; 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. (http://acqnotes.com/acqnote/tasks/risk-reporting-matrix)
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. (https://www.dau.edu/cop/log/Pages/Search.aspx?k=Risk Identification)

Name	Description	Purpose
Systems and software engineering framework and common process framework	A companion standard that provides detailed definition, requirements, and evaluation criteria for the technical reviews and audits associated with DOD acquisition projects.	Provides program managers and acquisition officials with the definitions, requirements, and evaluation criteria for conducting technical reviews and audits associated with DOD acquisition projects. DOD has adopted the Institute of Electrical and Electronics Engineers (IEEE) 15288.2, "IEEE Standard for Technical Reviews and Audits on Defense Programs" for describing the life-cycle of man-made systems and defines a set of Systems Engineering processes and associated terminology typical for the full system life-cycle, including conception, development, production, utilization, support, and retirement. A forthcoming revision to Chapter 4 of the Defense Acquisition Guidebook will refer to the IEEE standard rather than to the systems engineering technical review checklists. (https://www.acq.osd.mil/se/docs/15288-Guide-2017.pdf)
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.	Helps technology developers plan 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-20-48G

A best practices checklist that includes the corresponding high-quality characteristics related to using the TRA report findings is included below.

Best Practice Checklist: Using the TRA Report Findings

- The TRA report is used for its stated purpose, such as to inform decision makers about whether a prescribed TRL goal has been met, identify potential areas of concern or risk, or other. (Useful)
- For CTs assessed as immature and which did not meet the TRL goal: (Useful)
    - an alternate or backup technology is identified,
    - a technology maturation plan is developed,
    - the program's risk management plan is updated, and
    - the cost and schedule risk assessments are revised or updated.
- TRA reports used for governance purposes are prepared and submitted in advance of a decision point or stage gate so the information is timely and can be acted upon. (Useful)
- The TRA report documents lessons learned. (Reliable)

Technology Maturation Plans

The technology maturation plan (TMP) is a management planning tool to mature CTs that have been assessed as immature. The purpose of the TMP is to develop a plan to mature CTs to an acceptable TRL. The TMP lays out the steps, actions, and resources needed to mature CTs and uses the TRA report findings and other key information to establish a road map with the necessary engineering activities to mature the CTs. It provides an accurate gauge of the overall progress for maturing technology. The TMP also serves as a key reference document at a decision point or stage gate to verify that progress has been made in closing the maturity gaps.

There are a number of steps involved in preparing the TMP, including collecting information 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 the CTs.[56] CTs may change during development, and technology maturation test results may drive significant design changes. As a result, the TMP is a “living” document that is modified periodically as knowledge increases and as cost and schedule evolve with the maturity of CTs.

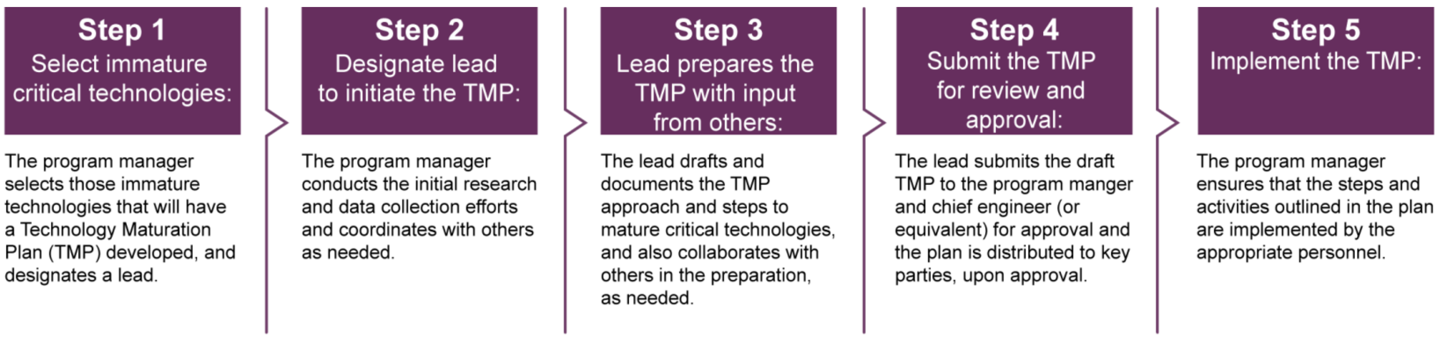
Program managers should mature CTs before system development begins. TMPs can be a standalone source of information or part of a broader set of documents, such as a project execution plan or technology development strategy.

Five Steps for Preparing the TMP

The TMP consists of five steps to mature CTs. The execution of these steps is commonly led by the program manager, who typically designates a planning lead with the knowledge to perform and facilitate the necessary work to develop the TMP. Figure 13 describes the five steps. Organizations may tailor them to accommodate their own structures, processes, and policies.

[56]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 acceptable TRL.

Figure 13: Five Steps to Prepare a Technology Maturation Plan (TMP)



Source: GAO analysis and subject matter expert input. | GAO-20-48G

Step 1

The program manager acknowledges the immature CTs cited by the TRA report and designates a planning lead to prepare the TMP. The program manager requires a TMP be prepared for the selected CTs. These CTs typically have a technology maturity gap. However, other technologies known to have challenges during development may also be selected. For example, a program manager may want a TMP prepared for technologies that pose greater risk due to their complexity or technologies for which there may be no baseline or history to draw observations on past performance.

Step 2

The program manager conducts initial research and data collection activities and then designates a lead to complete the TMP. Additional personnel may be provided to support the effort, such as engineering staff, contractor personnel, or subject matter experts, as needed. Initial research and data collection efforts start with the completed TRA report, and data collection and research efforts are conducted for each immature CT. The data collection activities include but are not limited to obtaining the current TRL rating for each CT from the TRA report and gathering additional 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 CTs. For this step, the planning lead may be from the program management team or engineering team but should coordinate with others to assist as needed.

Step 3

The planning lead drafts and documents the TMP.[57] The TMP should include the approach for defining the technology development activities, scoping the effort, and identifying the steps for bringing CTs to the desired maturity. In general, the required technology development activities and specific maturation plans are prepared for each CT identified by the program manager or engineering expert in Step 1. The lead recruits others as necessary to help develop the approach, activities, and steps for the TMP.

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 CT. 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 to the next step.[58] For example, the initial TMP is documented and approved and serves as a baseline for guiding the work. The TMP is maintained within the appropriate organization for future reference and updates.

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.

TMP Updates

The TMP is a "living" document that should be updated as progress is made, new information comes to light, or conditions that materially affect the plan occur. 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

[57]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.

[58]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.

completion before the next TRA. The updated TMP serves as a source document as part of a TRA for the assessment team. The five steps in figure 13 may be tailored to include steps for updating the TMP.

Sections of a Technology Maturation Plan

The TMP has three sections that document information to mature CTs. These sections are intended to document: (1) past TRAs and the most current TRLs; (2) a plan to mature technologies; and (3) a plan to mature the integration of CTs and technology elements that constitute the system.

Section 1 of the TMP called *Technology Assessments of the Project* is 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 TRLs for each CT is also included in this section.

Section 2 of the TMP called *Technology Maturation Plan* describes the approach, steps, and activities for maturing technologies, including the consideration of 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);
- the 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. The elements that 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 TMPs, program managers can consider these alternatives if efforts to reach certain TRL goals prove more challenging than expected. For example, if CTs 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. Case study 7 highlights the importance of establishing plans for backup technologies to keep a project on schedule. Advance planning can help program managers respond to unanticipated challenges without compromising performance goals.

Case Study 7: Identifying Alternative Critical Technologies, an Example from DOD, cited in GAO-08-467SP

In 2008, GAO reported that none of the Navy's P-8A Multi-mission Maritime Aircraft's initial four critical technologies were mature when it entered development. The P-8A 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. The P-8A program updated all four critical technologies identified at the program's start in 2004 in response to a 2006 TRA that found these technologies immature. It effectively mitigated risk by refocusing efforts on critical technologies that, it was believed, would better achieve program requirements. Further, the P-8A was to undergo structural modifications while on the production line in order to reduce time and cost. While the program experienced a $1.2 billion contract cost increase and the contractors estimated a 7-14 month delay for the build and delivery dates, it was not possible to predict the effect of a cost overrun had the program maintained the original critical technologies. However, the TRA is likely to have identified risks in time to inform future program decisions and minimize cost and schedule effects.

Source: U.S. Navy. | GAO-08-467SP

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

In preparing plans to mature each CT, programs should identify:

- the key technologies being addressed;
- the objectives of the technology development;
- the technology development approach;
- the scope, including;
    - specific tasks to be undertaken and
    - results needed for a claimed advancement to a higher TRL
- the responsible organization for the maturation activities;
- the TRL goals for each major milestone;
- the 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
- the off-ramps that will be taken if results are less than required at each critical decision milestone.

Developing plans to mature CTs 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.

Section 3 of the TMP called *Technology Maturity Schedule,* and *Summary Technology Maturity Budget* describes the plan to mature the technologies with the integration of the CTs, including an analysis of the maturity gaps. This section should include a high-level schedule and budget, including the total maturation costs for the major development activities for each CT. Major decision points, such as proceeding with or abandoning the current technology or selecting a backup technology, should be identified in this section. Figure 14 shows the TMP template with the detailed elements to include in the plan, along with a description of each element.

Figure 14: Technology Maturation Plan (TMP) Template

TECHNOLOGY MATURATION PLAN (TMP) TEMPLATE

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.

Source: GAO analysis of agency documents. | GAO-20-48G

Part 1 of 2

Figure 14: Technology Maturation Plan (TMP) Template (continued)

TECHNOLOGY MATURATION PLAN (TMP) TEMPLATE *(continued)*

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 acceptable 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 (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**
  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 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

Source: GAO analysis of agency documents. | GAO-20-48G Part 2 of 2

Organizations can tailor the TMP to accommodate their own terms, definitions, and processes.

A best practices checklist for preparing the TMP is included below.

Best Practice Checklist: Technology Maturity Plans

- The program manager appoints a lead planner with the knowledge, and experience to develop a credible TMP.
- The TMP includes the following elements:
  - a roadmap with detailed plans, steps, and actions for each CT;
  - associated risks (cost, schedule, and technical) for reaching the desired TRL for each CT, including the identification of back up technologies, as appropriate;
  - a high-level schedule and budget to mature each CT; and
  - program manager and chief engineer review and approval.
- The TRA report, analyses, and other credible information is used to support the TMP.
- The TMP is periodically updated.

TRAs and Software Development

Historically, the TRL scale has not always been understood in terms of what needs to be demonstrated for software at each of the nine TRLs because software development may not start until later in the acquisition life-cycle than hardware-related efforts. However, knowledge has increased over the last decade on how to better manage software development by placing greater emphasis on the use of prototypes, among other risk reduction practices.[59]

While some experts have noted that certain assessment tools are not well suited to evaluate software development efforts, new assessment tools or variations of existing ones are being used to do TRAs on software projects. This chapter briefly describes the current state of practice for evaluating the maturity of software technologies with a goal of creating awareness and opportunities for advancing knowledge. Appendix IV includes TRLs that describe software readiness levels.

Application of TRAs to Software Systems

Software has unique characteristics that make it inherently challenging to evaluate in contrast to hardware systems. For example, software is intangible whereas hardware has physical properties that can be more easily characterized, measured, monitored, and tested. Therefore, the data and information used to measure, monitor, manage, and control software is fundamentally different.

In general, project management challenges can be offset by early planning efforts and involving subject matter experts in the TRA process, especially when it comes to software. Experts noted that if technology developers and program managers do not take the appropriate actions upfront, such as involving software engineers earlier in the acquisition life-cycle, then projects are likely to encounter problems. Examples of technical and program management challenges that could potentially hamper software development efforts include

- Software is not routinely considered in planning, so it is often not identified early.

[59]Guidance for software TRL definitions is in DDR&E, U.S. Department of Defense, *Technology Readiness Assessment (TRA) Deskbook* (Washington, D.C.: 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 software technology is critical.
- Definitions are inconsistent as to what identifies new software technology as a CT. Reused software code or modified commercial off the shelf 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 can be overcome with knowledge, clearly articulated guidance, and subject matter experts with the appropriate expertise, skills, and experience. Experts who helped develop this Guide assert that the following questions could help facilitate improvement in the practice of assessing the software maturity.

- How well defined is the intended application? (This determines 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 identified and collected as a universal practice when evaluating software?
- Have software methodologies been documented? Are the acquisition life-cycle needs included in the software development plan?
- Has a structured or a disciplined process been followed?
- Have the effects of Agile software development methodologies been considered? Have the artifacts produced relative to the acquisition life-cycle been identified? For example, a traditional preliminary design review may not be feasible for organizations using Agile software development methodologies. In such cases, what body of evidence is sufficient to demonstrate progression has been made at these reviews?
- Does the TRA team 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

During development of this Guide, knowledge and information about TRAs when it comes to software-only technologies were evolving. According to experts, this is largely because embedded software maturity can be judged through hardware demonstrations using existing TRL concepts and definitions, whereas evaluations for software-only systems lack physical properties for observation. In addition, for software-embedded systems in which code is installed in the hardware, 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 be better assessed.

Software-only technologies where software “is” the standalone system and there is no hardware component may require more complicated, shorter acquisition life-cycle processes in contrast to embedded software systems that have specific requirements imposed by hardware constraints. In the software-only domain, methodologies typically involve iterative development, with a need to be more flexible, and involve early planning and incremental testing.

Given the complexity of software, opportunities exist to increase knowledge for improving the current state of practice with software systems or technologies. According to experts, better descriptions of the kinds of supporting evidence needed to demonstrate certain levels of maturity could improve the practice. While organizations continue to learn about how best to evaluate CTs when dealing with software, we believe that identifying and documenting lessons learned, establishing best practices, and sharing knowledge through communities of practice will improve TRAs on software development projects.

In addition, experts identified two key practices for conducting TRAs on software technologies as (1) including a software engineer on the TRA team with the requisite skills, experience, and knowledge to assess the software, and (2) ensuring that the appropriate types of evidence are identified as demonstration criteria for reaching a defined maturity level.

Development of System-level Readiness Measures

Applying TRA methods for evaluating the integration of technologies into a system or the readiness of larger systems or systems-of-systems has long been an area of interest among the systems engineering community, as well as within the TRA expert community. Many experts believe that the integration of CTs into such systems is captured in the readiness levels of the TRL scale where a technology should be demonstrated in a system in its proposed operational environment. However, practitioners have expressed concern about using the results of TRAs performed on a few technologies to determine the readiness of systems with numerous technologies, components, and integrations. Experts realize that additional system-level measures are needed to advance knowledge and evaluate the readiness of today's complex systems.

Presented in 2006 by the Systems Development and Maturity Laboratory at Stevens Institute of Technology, the system readiness level (SRL) was designed to give a holistic picture of the readiness of complex systems by characterizing the effect of technology and integration maturity on a systems engineering effort. The method was proposed because TRLs measure the maturity of an individual technology but do not provide insight into integration between technologies or the maturity of the whole system. The SRL incorporates the current TRL scale and introduces an integration readiness level (IRL) to calculate the SRL.[60, 61] Considerable work has been done over the last several years to enhance and improve the original SRL methodology creating what is hoped will be an emerging systems engineering best practice, the Systems Readiness Assessment (SRA) methodology. This methodology is captured in detail and documented in the SRA Engineering Handbook.[62]

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[60]An SRL measures the readiness of the whole system or all of the components of the system integrated together. The measure is designed to give a holistic picture of the readiness of complex systems by characterizing the effect of technology and integration maturity on a systems engineering effort. The concept of the SRL incorporates the TRL scale and introduces the IRL to calculate the SRL. There are nine levels that range from a SRL 1 where the system alternative materiel solutions should have been considered to SRL 9 where the system has achieved initial operational capability and can satisfy mission objectives.

[61]Sauser, Brian J. and Ramirez-Marquez, Jose E., *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).

[62]System Readiness Assessment (SRA) Engineering Handbook, International Systems Readiness Assessment (SRA) Community Of Interest (ISRACOI), October 2017.

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 is 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. The readiness of each technology of the system and all of its integrations are then mathematically combined, resulting in a system-level readiness measure, the SRL. The methodology can be adapted for use in an array of system engineering development efforts and can also be applied as a tool for technology insertion trade studies and analysis. As with knowledge-building TRAs, performing multiple SRAs over the life-cycle can identify potential problem areas and help to reduce program risk.

A SRA user environment tool has been developed and deployed that provides an interactive environment to model a system's architecture and integrations and calculate the system's readiness. The user environment allows for the visualization and monitoring of a system's development progress and its associated readiness over time. Tools have also been developed using Bayesian network models to provide a mathematically consistent method for validating both the TRL and IRL, increasing the confidence in the determination of the readiness of system components and their technologies.[63, 64] The SRA user environment and the TRL and IRL Bayesian network models have all been open sourced and are publicly available. Appendix V lists other types of readiness levels for evaluating the integration of technologies.

While the SRA methodology has been implemented successfully on several development programs, the methodology does not have as an extensive history of use and application as does the TRA. A number of experts who helped develop this Guide have formed the International Systems Readiness Assessment Community of Interest (ISRACOI), a worldwide collaborative community of individuals from industry, academic,

[63]Austin, Marc F., Homberger, Cheyne, Ahalt, Virginia, Doolittle, Erin, Polacek , George, York, Donald M., *Applying Bayesian Networks to TRL Assessments – Innovation in Systems Engineering*, (presented at the 27th Annual INCOSE International Symposium, Adelaide, Australia, July 15-20, 2017).

[64]Austin, Marc F., Ahalt, Virginia, Doolittle, Erin, Homberger, Cheyne, Polacek ,George A, York, Donald M., *Mitigating Integration Risks in Complex Systems," (*presented at the 28th Annual INCOSE International Symposium, Washington DC, July 7-12, 2018).

and government 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, the SRA user environment, and the TRL and IRL Bayesnet tools. For more information about ISRACOI and key initiatives, go to http://www.ISRACOI.org.

Glossary

Critical technology (CT) - is a new or novel technology, or technology being used in a new or novel way, that is needed for a system to meet its operational performance requirements within defined cost and schedule parameters.

Governance body - an individual or group of individuals charged with program oversight in managing and allocating fiscal resources as the gatekeeper for the organization.

Heritage technologies - technologies that have been used successfully in operation. Such technologies may be used in new ways where the form, fit or function is changed; the environment to which it will be exposed in its new application is different than those for which it was originally qualified, or process changes have been made in its manufacture.

Knowledge-building TRA - a tailored self-assessment intended for a narrower audience, such as the program manager, or technology developer where the focus of the TRA may be to gauge progress toward achieving a certain technology maturity goal, evaluate technology maturity, or identify and manage risk. Systems engineers may use them to understand the risks before integrating technologies into new or existing acquisition programs.

Major decision point - used to describe a point in an acquisition project or plan at which development can be examined and any important changes or decisions relating to costs, resources, profits, etc. can be made. In private industry, not for profit, and other sectors these points may be referred to as “stage gates.”

Operational environment - an environment that addresses all the operational requirements and specifications required of the final system to include platform/packaging.

Relevant environment - a test environment that simulates both the most important and most stressing aspects of the operational environment.

Simulated environment - a device, computer program, or system that performs a simulation of an environmental model. The simulated environment is used to test CTs and evaluate their function and operation in a technology’s demonstrated readiness.

Technical baseline description - a document that describes the program or project's purpose, system, performance characteristics, and system configuration.

Technology readiness assessment (TRA) - a systematic, evidence-based process that evaluates the maturity of CTs (hardware, software, processes, or a combination thereof) that are vital to the performance of a larger system or the fulfillment of the key objectives of an acquisition program.

Technology maturity assessment strategy - a best practice approach for large acquisition programs where multiple TRAs and other assessments are identified in a program's overall acquisition strategy plan.

Technology maturation plan (TMP) - a management planning tool that lays out the steps, actions, and resources needed to mature CTs that have been assessed as less mature than desired or are lagging in maturity compared to other CTs.

Technology readiness levels (TRL) - a scale that consists of nine levels ranging from one through nine—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. The scale is ordered according to the characteristics of the demonstration or testing environment under which a given technology was tested at defined points in time.

Appendix I: Objectives, Scope, and Methodology

To ascertain generally accepted best practices for conducting high-quality TRAs of technologies, we conducted knowledge sharing meetings with practitioners and technology experts from across the federal government, commercial industry, nonprofits, and academia. We conducted periodic in-person meetings at our headquarters building in Washington D.C., as well as virtual meetings with a community of over 180 experts where we collected information, facilitated focus groups, and elicited feedback on iterative drafts of the Guide's chapters. To ensure the Guide reflected a broad range of knowledge and viewpoints in order to identify useful information to more effectively mature critical technologies, determine critical technology readiness and address risk, we consulted experts from the science and technology, systems engineering, nuclear engineering, software and computer sciences, risk management, and acquisition policy and program management disciplines. We released a public exposure draft of the *GAO Technology Readiness Assessment Guide* (GAO-16-410G) in August 2016 for a 12-month comment period.

From August 2017 to June 2019, we assembled a GAO expert panel made up of representatives from the Applied Research and Methods; Contracting and National Security Acquisitions; Information Technology and Cybersecurity; Natural Resources and Environment; and Science, Technology Assessment, and Analytics mission teams to adjudicate over 400 comments that we received during the public comment period. To update the exposure draft of the Guide, the GAO expert panel vetted each comment and placed it in one of two categories—as actionable where the comment could be further adjudicated, or as not actionable because the comment was either not in alignment with the broader opinion of the expert community, outside the Guide's scope, factually incorrect, or provided no basis in which an actionable response could be taken. For each actionable comment, we documented the GAO expert panel decisions on how each was addressed in the Guide.

We conducted our work from January 2013 to December 2019 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to our objectives. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations in our work. We believe that the information and data obtained, and the synthesis of information conducted, provide a reasonable basis for the guidance in this product.

Appendix II: Key Questions to Assess How Well Programs Followed the Five Step Process for Conducting a TRA

Following best practices helps ensure that the TRA reflects all of the high-quality characteristics of credibility, objectivity, reliability, and usefulness. We have identified five steps that, when followed correctly, should result in TRAs that governance bodies or program managers or technology developers can use for making informed decisions.

The following questions correlate to the best practice checklists from the Guide's five steps of conducting a high-quality TRA. These questions can be used by auditors or other independent entities that may be internal or external to an organization to evaluate the extent to which the best practices have been met.

Step 1 –Prepare the TRA Plan, and Select the TRA Team

1.1 Does the TRA plan have a comprehensive assessment approach that includes the following?

1. Is the purpose and scope clearly defined?
2. Are the resources, schedule, funding, and personnel needed to conduct the TRA identified?
3. Are the CT definition and TRL definitions identified?
4. Are the evaluation criteria to be used for assessing test results defined? Does it describe the types of evidence that will be collected to perform the assessment? Who will write the TRA report?
5. Is there a written study plan to help each TRA member prepare for conducting the assessment?
6. Is there a plan for handling dissenting views?

1.2 Does the TRA plan identify the recipient(s) of the report, such as a program manager, systems engineer, or a governance body supporting an upcoming decision point, stage gate, or go/no-go decision?

1.3 Does the TRA plan identify the expertise needed to conduct the assessment, and other characteristics of the TRA team, such as

1. Is the composition of the expertise, knowledge, and experience needed to conduct the TRA clearly written to guide the selection of the TRA team members?
2. Is the TRA team defined and properly sized to conduct the assessment? What was the basis for the sizing the TRA team?

3. Are the TRA team members experienced in conducting TRAs? For those team members with TRA experience, what are those experiences, qualifications, certifications, and training?
4. Are the TRA team member profiles documented and do they include signed statements of independence?
5. Did the TRA team have access to or discuss the need for additional subject matter experts from a variety of disciplines as needed or determined by the team? If so, who were those experts and in which disciplines were they experienced?

1.4 Are members of the TRA team independent and objective? Have they signed statements of independence?

1.5 Did the TRA team review the initial TRA plan to ensure it included all the essential information?

1.6 Has the TRA team been allocated adequate time and resources to execute the TRA plan?

1.7 Has the appropriate information been obtained and documented to conduct the TRA, such as the program master schedule, budget documents, test plans, and a technical baseline description of the program's purpose, system, performance characteristics, and system configuration?

1.8 Is the level of detail in the TRA commensurate with the level of detail available for the program?

Step 2 – Select the Critical Technologies

2.1 In selecting CTs, was a reliable, disciplined, and repeatable process followed and documented?

2.2 In selecting CTs, was the decision based on consideration of the newness or novelty of technologies and how they will be used?

2.3 In selecting CTs, was the selection based on consideration of the operational performance requirements and potential cost and schedule drivers?

2.4 For each CT is the relevant environment derived based on those aspects of the operational environment determined to be a risk for the successful operation of the technology?

2.5 Did the selection of CTs consider the potential adverse interactions with system interfaces?

2.6 Is the number of CTs selected for assessment based on solid analysis using the WBS, technical baseline description, process flow diagram, or other key program documents?

2.7 Is the selection of CTs confirmed using more specific questions and requirements that pertain to the platform, program, or system in which they will operate, refined and confirmed by the TRA team and others, as appropriate?

2.8 Are CTs selected during early development?

2.9 Are CTs defined at a testable level, including any software needed to demonstrate the functionality?

2.10 Did the TRA team document the reasons why technologies were selected as critical and why other technologies were not selected?

Step 3 – Evaluate the Critical Technologies

3.1 Did the TRA team confirm that the TRL measure and definitions selected during the TRA planning phase was appropriate? Did the TRA team reach agreement with the program manager on the kinds of evidence that would be needed to demonstrate that a TRA goal or objective has been met?

3.2 Did the TRA team interview the testing officials and verify that the test article and the relevant or operational environment are acceptable and the results acceptable?

3.3 For the assigned TRL rating for each CT, did the TRA team document and support their decisions with credible and verified evidence, such as test analytical reports, requirements documents, schematics, and other key documents?

Step 4 – Prepare the TRA Report

4.1 Is there a policy or guidance on how TRA reports should be prepared, including a template that identify the elements to report and document; process for submission, review, and approval; how the TRA results should be communicated; and who should be involved?

4.2 Does the TRA report include the following key information: (1) executive summary of the rating, (2) program background information, (3) TRA purpose and scope, (4) process for conducting the TRA, including the selection of CTs, (5) rating for each CT assessed, (6) supporting evidence for each CT assessed including references to test results and other key documents, and (7) executive staff approval of the TRA report rating?

4.3 Upon completion of the assessment by the TRA team, did management check or attest the factual accuracy of the TRA report?

4.4 Does the TRA report include management's response (i.e., concurrence, or dissenting views with the findings)? Is the response clearly written, logical, and supported by evidence to support the position?

Step 5 –Use the TRA Report Findings

5.1 Was the TRA report used for its intended purpose, such as to inform decision makers about whether a prescribed TRL goal has been met, identify potential areas of concern or risk, or other purpose?

5.2 For CTs that are assessed as immature and did not meet the TRL goal, which of the following actions were taken?

1. Identify alternative or backup technologies?
2. Initiated development of a TMP?
3. Update the program risk management plan?
4. Update the cost and schedule risk assessment?

5.3 For TRA reports used for governance purposes, was the report timely? (e.g., submitted in advance of the decision point or stage gate to allow sufficient time to use the information)

5.4 Does the TRA report document lessons learned?

Appendix III: Case Study Backgrounds

The Guide's case studies are from GAO reports described in this appendix. Table 6 shows the relationship between the case study, GAO report and the page number where they can be found. The table is arranged by the order in which they appear. Following the table, paragraphs describe the reports and are ordered by the case study number as they appear in the Guide.

Table 6: GAO Reports Used as Case Study in the TRA Guide

Case Study	GAO report	Page no.
1	GAO-19-336SP: GAO, *Weapon Systems Annual Assessment: Limited Use of Knowledge-Based Practices Continues to Undercut DOD's Investment*	21
2	GAO-08-408, *Defense Acquisitions: 2009 is a Critical Juncture for the Army's Future Combat System*	28
3	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*	29
4	GAO-07-96, *Space Acquisitions, DOD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems*	30
5	GAO-02-201, *Defense Acquisitions: Steps to Improve the Crusader Program's Investment Decisions*	49
6	GAO-18-158: *Columbia Class Submarine: Immature Technologies Present Risks to Achieving Cost, Schedule, and Performance Goals*	51
7	GAO-08-467SP, *Defense Acquisitions: Assessments of Selected Weapon Programs*	92

Source: GAO website. | GAO-20-48G

Case Study 1: Knowledge-Building TRAs Inform Acquisition Strategies, GAO-19-336SP

In 2019, the Navy was determining the acquisition strategy for the Next Generation Jammer Low-Band program and analyzing potential solutions to meet its capability needs. The program is an external jamming pod system that will be fitted on EA-18G Growler aircraft in order to disrupt adversaries' use of the electromagnetic spectrum for radar detection, among other purposes. The Navy was planning to execute the program as a middle tier acquisition. A middle tier acquisition—also referred to as a Section 804 program—is a program that uses a streamlined acquisition process to rapidly prototype or field capabilities within a 5-year period. One of the factors program officials considered to determine whether the program would move forward as a middle tier acquisition was the technology maturity of critical technologies to be used on the program.

The Navy used a technology maturity assessment process it cited as a best practice to inform the program of any technology maturity concerns prior to it making key decisions about its acquisition strategy. According to the Navy, in October 2018, two contracts were awarded to assess maturity of technologies, identify potential materiel solutions, and inform acquisition strategy development. Both contractors were required to provide technology demonstration prototypes and demonstrate technology maturity in a relevant test environment. In July 2019, an independent Navy assessment team conducted technology maturity assessments of both contractors' prototype designs using a process it described as having the rigor and discipline of a TRA. We refer to these types of assessments as knowledge-building TRAs. The team examined contractor self-assessments based on technical work breakdown structures and supplemental information from the contractors to perform its assessments. Based in part of the results of these assessments, the program proposed moving forward as a middle tier acquisition program.

See, GAO, *Weapon Systems Annual Assessment: Limited Use of Knowledge-Based Practices Continues to Undercut DOD's Investments*, GAO-19-336SP, May 2019. Subsequent follow-on work was conducted for this case study.

Case Study 2: 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 FCS concept and software, and a cost estimate and affordability assessment.

Maturing technologies to 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 reported that FCS's critical technologies remained at low TRLs 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, GAO, *Defense Acquisitions: 2009 Is a Critical Juncture for the Army's Future Combat System*, GAO-08-408, March 2008.

Case Study 3: Assessments Needed to Provide Better 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 reported that the U.S. 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 4: Space Programs Often Underestimate Costs, GAO-07-96

In 2006, GAO reported 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 National Polar-orbiting 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 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 5: 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 reported 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 reported 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 6: Narrow View of Critical Technologies Can Result in Underrepresentation of the Technical Risks, GAO-18-158

The Navy's Columbia class ballistic missile submarines will replace the 14 Ohio class that currently provide the sea-based leg of the U.S. nuclear triad, slated to begin retiring in 2027. Additional development and testing are required to demonstrate the maturity of several Columbia class submarine technologies that are critical to performance, including the Integrated Power System, nuclear reactor, common missile compartment, and propulsor and related coordinated stern technologies.

The Columbia-class submarine program is a $126 billion effort to build 12 nuclear powered ballistic missile submarines. We used the criteria from GAO's TRA Guide to evaluate the quality and completeness of the Navy's assessment of technology readiness and risk. GAO found that the Navy underrepresented the program's technology risks in its 2015 TRA when it did not identify several technologies as critical. In 2017, GAO reported that the Navy did not follow our identified best practices for identifying critical technologies for the program, resulting in an underrepresentation of the technical risk. Development of these technologies is key to meeting cost, schedule, and performance requirements. A high-quality TRA serves as the basis for realistic discussions on how to mitigate risks as programs move forward from the early stages of technology development. Not identifying these technologies as critical means Congress may not have had the full picture of the technology risks and their potential effect on cost, schedule, and performance goals as increasing financial commitments were made.

GAO, *Columbia Class Submarine: Immature Technologies Present Risks to Achieving Cost, Schedule, and Performance Goals*, GAO-18-158, December 2017.

Case Study 7: 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

In 2008, GAO reported that none of the Navy's P-8A Multi-mission Maritime Aircraft's initial four critical technologies were mature when it entered development in May 2004. At the time, 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. Since then, the program removed one critical technology, replaced it with backups, and added a new critical technology. 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: Examples of Various TRL Definitions and Descriptions by Organization

Table 7: 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-20-48G.

Table 8: 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.

TRL	Definition	Description
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-20-48G.

Table 9: 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.

TRL	Definition	Description
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-20-48G

Table 10: 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.

TRL	Definition	Description
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-20-48G

Table 11: 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.

TRL	Definition	Description
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.
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-20-48G

Table 12: Department of Transportation Technology Readiness Levels (2017)

	TRL	Description	To achieve the given TRL, you should answer yes to EVERY question. Discuss any uncertain answers.
Basic Research	1	Basic principles and research	Do basic scientific principles support the concept? Has the technology development methodology or approach been developed?
	2	Application formulated	Are potential system applications identified? Are system components and the user interface at least partly described? Do preliminary analyses or experiments confirm that the application might meet the user need?
	3	Proof of Concept	Are system performance metrics established? Is system feasibility fully established? Do experiments or modeling and simulation validate performance predictions of system capability? Does the technology address a need or introduce an innovation in the field of transportation?
Applied Research	4	Components validated in laboratory environment	Are end-user requirements documented? Does a plausible draft integration plan exist, and is component compatibility demonstrated? Were individual components successfully tested in a laboratory environment (a fully controlled test environment where a limited number of critical functions are tested)?
	5	Integrated components demonstrated in a laboratory environment	Are external and internal system interfaces documented? Are target and minimum operational requirements developed? Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?
Development	6	Prototype system demonstrated in a relevant environment	Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? Was the prototype tested in a realistic and relevant environment outside the laboratory? Does the prototype satisfy all operational requirements when confronted with realistic problems?
	7	Prototype demonstrated in operational environment	Are available components representative of production components? Is the fully integrated prototype demonstrated in an operational environment (i.e., real-world conditions, including the user community)? Are all interfaces tested individually under stressed and anomalous conditions?
	8	Technology proven in operational environment	Are all system components form-, fit-, and function-compatible with each other and with the operational environment? Is the technology proven in an operational environment (i.e., meet target performance measures)? Was a rigorous test and evaluation process completed successfully? Does the technology meet its stated purpose and functionality as designed?

	TRL	Description	To achieve the given TRL, you should answer yes to EVERY question. Discuss any uncertain answers.
Implementation	9	Technology refined and adopted	Is the technology deployed in its intended operational environment? Is information about the technology disseminated to the user community? Is the technology adopted by the user community?

Source: GAO presentation of Department of Transportation information. | GAO-20-48G

Appendix V: Other Types of Readiness Levels

Manufacturing readiness levels (MRLs). Used in conjunction with TRLs, MRLs are key measures that define 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 also be used to define manufacturing readiness and risk at the system or subsystem level. For those reasons, the MRL criteria were designed to include a nominal level of technology readiness as a prerequisite for each level of manufacturing readiness. Although the MRLs are numbered, the numbers themselves are unimportant. The numbers represent a non-linear ordinal scale that identifies what maturity should be as a function of where a program is in the acquisition life-cycle. Using numbers is simply a convenient naming convention. Table 14 shows a short summary of the full criteria and metrics for each of the 10 MRLs (numbered 1 through 10).[1]

Table 13: 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.

[1]For additional information about manufacturing readiness, and details in the MRL Matrix, see, Department of Defense, *Manufacturing Readiness Level (MRL) Deskbook*, (Washington, D.C.,: 2018) (*http://www.dodmrl.com/).*

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 Maturation & Risk Reduction 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. Manufacturing, material, and special requirement cost drivers have been identified, and cost driver uncertainty has been qualified. Producibility assessments of design concepts have been completed. Key performance parameters have been identified as well as any special tooling, special handling, manufacturing skill sets, and workforce requirements and availability of facilities.
5	Capability to produce prototype components in a production relevant environment	This level of maturity is typical of the mid-point in the Technology Maturation & Risk Reduction 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 a minimum TRL 5. The industrial base assessment should have been initiated to identify potential manufacturing sources. The manufacturing strategy developed for the Milestone A Acquisition strategy has been refined with the technology maturation contractor and integrated into the risk management plan. Identification of enabling/critical technologies and components is complete. With release of product data required for prototype component manufacturing, evaluation of the design to determine Key Characteristics has been initiated. Prototype materials have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts, as well as producibility assessments of key technologies and components have been initiated.
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. Manufacturing processes and manufacturing technology solutions, materials, tooling and test equipment, as well as personnel skills have been demonstrated on components, subsystems, and/or systems 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 developed appropriate risk reduction strategies to achieve cost requirements. Producibility trade studies and producibility considerations have shaped system development plans. Industrial capabilities assessment 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 CDR. Technologies should be assessed at a minimum of 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 produced in a production relevant environment, 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 efforts are initiated and validation plans for Special Test Equipment/ Special Inspection Equipment (STE/SIE) are complete.
8	Pilot line capability demonstrated; ready to begin Low Rate Initial Production (LRIP)	This level is associated with readiness for a Milestone C decision, and entry into LRIP or initial production. Technologies should have matured to at least TRL 7 or 8. Detailed system design is complete and sufficiently stable to enter low rate production. All materials, manpower, tooling, test equipment, and facilities are proven on the pilot line and are available to meet the planned low rate production schedule. STE/SIE has been validated as part of pilot line validation in accordance with validation plans. Manufacturing and quality processes and procedures have been proven on a pilot line and are under control and ready for low rate production. Known producibility risks and issues 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 inspections have been completed. The industrial base has been assessed for Milestone C and shows industrial capability is established to support LRIP.
9	Low rate production demonstrated; Capability in place to begin Full Rate Production (FRP)	At this level, the system, component, or item is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 8 or 9. This level of readiness is normally associated with readiness for entry into FRP (rate production). 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 operational test and evaluation. Materials, parts, manpower, tooling, test equipment, and facilities are available to meet planned rate production schedules. STE/SIE validation maintained and revalidated as necessary. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet KC tolerances. Risks and issues managed with monitoring ongoing. LRIP cost targets have been met, and learning curves have been analyzed with actual data. The cost model has been updated for FRP and reflects the impact of continuous improvement.
10	Full Rate Production demonstrated and lean production practices in place	This is the highest level of manufacturing readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production & Deployment or Operations & Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to continuous improvement changes or obsolescence issues. System, components, and 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. STE/SIE validation maintained and revalidated as necessary. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Continuous process improvements are ongoing.

Source: GAO presentation of DOD information. | GAO-20-48G

Integration readiness level (IRL). This metric measures 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 reflect the DOD development approach.[2] 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 14: Integration Readiness Levels

IRL	Definition	Evidence Description
0	No integration	No integration between specified components has been planned or intended
1	A high-level 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 units 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
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.)

[2]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.(2008):, 39-58.

IRL	Definition	Evidence Description
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: Marc Austin, and Donald York, Conference on System Engineering Research. | GAO-20-48G

System readiness levels (SRL). The SRL index is a function of the individual TRLs in a system and their subsequent integration points with other technologies, IRL. The function of this interaction correlates to a nine level SRL index. The SRL index is 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 15: 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
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

Level	SRL Definition
2	System materiel solution should have been identified
1	System alternative materiel solutions should have been considered

Source: GAO presentation of NSA SRA Handbook SRL information. | GAO-20-48G

Appendix VI: Agency Websites where TRA Report Examples can be Found

Department of Defense
(http://acqnotes.com/acqnote/acquisitions/technology-readiness-assessment)

Department of Energy
(https://www.energy.gov/sites/prod/files/em/Volume_I/O_SRP.pdf)

Department of Transportation
(https://highways.dot.gov/exploratory-advanced-research/research/technology-readiness-assessment-work-ear-program)

Appendix VII: 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 TRA Guide. They attended and participated in numerous expert meetings, provided text or graphics, and submitted substantial comments.

Table 16: Experts Who Made Significant Contributions

Organization	Expert
Boeing	Chahriar Assad
Department of Defense	Marc Austin
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 Analyses	Irv Boyles
Institute for Defense Analyses	David Sparrow
Intrepid Defense Systems	Mike Ellis (retired)
JB Consulting	Jim Bilbro
Lockheed Martin	Bradley Atwater
Lockheed Martin	Joe Uzdzinski
NASA	Faith Chandler
Naval Research Laboratory	Phillip Schwartz
Navy, Perspecta (ONR contractor support)	Chris Alberg
Navy, NAVAIR	Ed Copeland, Ph.D.
SAIC	Donald M. York
Terranear PMC	Jay Roach
Waymo	Matt Markel

Source: Technology Experts. |. GAO-20-48G

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

Table 17: Experts Who Made Noteworthy Contributions

Organization	Expert
Air Force Space and Missile Systems Center (Software Engineering Institute)	Edmund Conrow
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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	Ed Kraft
Air Force	Claudia Kropas-Hughes
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
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Boeing	Michael Rosenthal
Boeing	John Tracey
Boeing	Charles Woods
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Defense Acquisition University	William Decker
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Department of Defense	Nichelle Dent
Department of Defense	Mark Evans
Department of Defense (contractor)	Mike Grieco
Department of Defense (contractor)	David Hillman
Department of Defense (contractor)	Timothy Ingles
Department of Defense (contractor)	Stephen Letschin
Department of Defense (contractor)	Brian Mack
Department of Defense	Stephen Spear
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 Energy	Mark Arenaz
Department of Energy	Michael Cercy
Department of Energy	David Diddio
Department of Energy	Roland Frenck
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Hexagon US Federal	Willie McFadden II
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Honeywell Aerospace	Bob Rasmussen
Honeywell Aerospace	Bob Smith
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HRL Laboratories	Jeffrey William
Institute for Defense Analyses	Paul Kodzwa
Institute for Defense Analyses	Jay Mandelbaum
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Jacobs Engineering	Uwe Hueter
Johns Hopkins University	Russell Fink
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MCRI	Bill Chadwick
MCRI	Jason Dechoretz
MCRI	Brian Evans
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MIT	Alison Olechowski
MITRE	Alex Chu
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MITRE	Brigitta Rubin
MITRE	Lillian Ryals
MITRE	Pete Sherlock
MITRE	Jeff Stevens
MITRE	John Wilson
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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	Sandra Smalley
NASA	Joe Smith
NASA	Stephanie Stilson
NASA	Mike Tinker
NASA	David Voracek
NASA	Kulpa Vygantas
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Navy	Carly Jackson
Navy	Rich Volkert
Navy	Eric Wilson
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Northrop Grumman	Jerry Nolte (retired)
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
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Potomac Institute	Mike Swetnam
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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
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Source: Technology Experts. | GAO-20-48G

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Acknowledgments

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References

Ahalt, Virginia, Erin Doolittle, Cheyne Homberger. “Advances in System Readiness Assessment.” 84th Military Operations Research Society Symposium, 20-23 June 2016.

Austin, Marc, Virginia Ahalt, Erin Doolittle, Cheyne Homberger, George Polacek, and Donald York. “Mitigating Integration Risks in Complex Systems.” 28th Annual INCOSE International Symposium. Washington D.C., July 2018.

Austin, Marc, Cheyne Homberger, George Polaceck, Erin Doolittle, Virginia Ahalt, and Donald York.”Using Bayesian Networks to Validate Technology Readiness Assessments of Systems.” Disciplinary Convergence in Systems Engineering Research, pp. 787-797, November 26, 2017.

Austin, Marc, Cheyne Homberger, Virginia Ahalt, Erin Doolittle, George A. Polacek, and Donald York. Applying Bayesian Networks to TRL Assessments – Innovation in Systems Engineering. INCOSE, 27,no. 1, (July 2017): 1622-1634.

Austin, Marc, and Donald York. “System Readiness Assessment (SRA) – An Illustrative Example.” 13th Annual Conference on Systems Engineering Research (CSER). Hoboken, N.J., March 2015.

Austin, Marc, and Donald York. “System Readiness Assessment (SRA), A Vade Mecum.” Complex Systems Design and Management (CSDM) Conference. Paris, France, November 2015.

Austin, Marc, and Donald York. “System Readiness Assessment (SRA), A Vade Mecum.” Complex Systems Design and Management (CSDM) Conference. Paris, France, November 2015.

Austin, Mark, Cheyne Homberger, George Polacek, Erin Doolittle, Virginia Ahalt, and Donald York. “Using Bayesian Networks to Validate Technology Readiness Assessments of Systems.” 15th Annual Conference on Systems Engineering Research (CSER), Redondo Beach, CA, March 2017.

Austin, Marc, Donald York. “Bucketology and an Enterprise Approach to System of Systems Development.” IEEE System of Systems (SoS) Conference, Paris, France, 19-22 June 2018.

Azizian, Nazanin, Shahram Sarkani, and Thomas Mazzuchi. "A Comprehensive Review and Analysis of Maturity Assessment Approaches for Improved Decision Support to Achieve Efficient Defense Acquisition." Proceedings of the World Congress on Engineering and Computer Science, no. II, October 2009.

Bilbro, James. "Benefits and Limitations of Current Techniques for Measuring the Readiness of a System to Proceed to Production." PowerPoint presented at the INCOSE Huntsville Regional Chapter Monthly Meeting, 2010.

Bilbro, James. Systematic Assessment of the Program / Project Impacts of Technological Advancement and Insertion Revision A. George C Marshall Flight Center, December 2007.

Blanchette Jr., Stephen, Cecilia Albert, and Suzanne Garcia-Miller. "Beyond Technology Readiness Levels for Software: U.S. Army Workshop Report." Software Engineering Institute, Technical Report, CMU/SEI-2010-TR-044, ESC-TR-2010-109. December 2010.

Craver, Jeff, and Lt. Col. Dian Hall. "Best Practices in Defense Technology Development and Technology Maturity Assessments." PowerPoint Presentation at the Systems and Software Technology Conference, April 28, 2010.

Department of Defense, Defense for Research and Engineering. Technology Readiness Assessment (TRA) Guidance. Washington, D.C., April 2011.

Department of Defense, Defense Research and Engineering. Technology Readiness Assessment (TRA) Deskbook, Washington, D.C., July 2009.

Department of Defense, Defense for Science and Technology. Technology Readiness Assessment (TRA) Deskbook, Washington, D.C., May 2005.

Department of Defense, Defense for Science and Technology. Technology Readiness Assessment (TRA) Deskbook. Washington, D.C., May 12, 2003.

Ellis, Mike, and Jeff Craver. "Technology Program Management Model (TPMM), A Systems-Engineering Approach to Technology Development Program Management." Dynetics, Inc. October 26, 2006.

Fitzpatrick, William. “A Software Technology Readiness Assessment Process for Minimizing System Acquisition Risk.” PowerPoint Presentation, November 17, 2005.

Fitzpatrick, William, Richard Wyskida, and Robert Loesh. “Using the Technology Assessment Procedure to Assess, Manage, and Minimize Software Safety Risk. Department of Defense and National Aeronautics and Space Administration, 2005.

Homberger, Cheyne, Marc Austin, and Donald York. “System Readiness – A Look Beyond TRAs.” NDIA. October 2017.

Austin, Marc, Cheyne Homberger, George Polacek, Erin Doolittle, Virginia Ahalt, and Donald York. “Using Bayesian Networks to Validate Technology Readiness Assessments of Systems.” 15th Annual Conference on Systems Engineering Research (CSER), Redondo Beach, CA, March 2017.

Katz, Daniel, Shahram Sarkani, Thomas Mazzuchi, and Edmund Conrow. “The Relationship of Technology and Design Maturity to DOD Weapon System Cost Change and Schedule Change During Engineering and Manufacturing Development.” Systems Engineering 18, no. 1 (2015):,1–15.

Kramer, Corinne, Jay Mandelbaum, Michael May, and David Sparrow. Training Briefing for the Conduct of Technology Readiness Assessments. Institute for Defense Analyses, IDA Document D-4029. Washington, D.C., April 2009.

Mankins, John C. “Technology Readiness and Risk Assessments: A New Approach.” Acta Astronautica, no. 65, Issues 9-10 (November-December 2009): 1208-1215.

Mankins, John C. “Technology Readiness Assessments: A Retrospective.” Acta Astronaut, no. 65, Issues 9–10 (November-December 2009): 1216–1223.

Mankins, John C. “Approaches to Strategic Research and Technology Analysis and Road Mapping,” Acta Astronaut. no. 51, Issues. 1–9 (July-November 2002): 3–21.

Mazzuchi, Thomas, Nazanin Azizian, Shahram Sarkani, and David Rico. “A Framework for Evaluating Technology Readiness, System Quality, and

Program Performance of U.S. DOD Acquisitions." Systems Engineering 14, no. 4, (2011): 410–427.

National Aeronautics and Space Administration, Office of Space and Technology. Mankins, John C. Technology Readiness Levels: A White Paper. April 6,1995.

National Aeronautics and Space Administration, Office of the Chief Engineer. NASA Space Flight Program and Project Management Requirements (NPR 7120.5E). Effective date: August 14, 2012. Expiration date: August 14, 2020.

National Aeronautics and Space Administration. NASA Systems Engineering Handbook. Washington, D.C., December 2007.

National Aeronautics and Space Administration, Procedural Requirement (NPR) 7123.1B Appendix E (Technology Readiness Levels). Effective date: April 18, 2013. Expiration date: December 18, 2019.

Olechowski, Alison, Steven Eppinger, and Nitin Joglekar. "Technology Readiness Levels at 40: A Study of the State-of-the-Art Use, Challenges, and Opportunities." Portland International Conference on Management of Engineering and Technology, August 2015.

Sauser, Brian, Ryan Gove, Eric Forbes, and Jose Ramirez-Marquez. "Integration Maturity Metrics: Development of an Integration Readiness Level." Information Knowledge Systems Management , no. 9 (2010): 17-46.

Sauser, Brian, Jose Ramirez-Marquez, Romulo Magnaye, and Weiping Tan. "A Systems Approach to Expanding the Technology Readiness Level within Defense Acquisition." International Journal of Defense Acquisition Management, no. 1 (2008): 39-58.

Sauser, Brian, Jose Ramirez-Marquez, Dinesh Verma, and Ryan Gove. "From TRL to SRL: The Concept of Systems Readiness Levels". Conference on Systems Engineering Research, Los Angeles, CA, April 2006.

Tomaschek, Katharina, Alison Olechowski, Steven Eppinger, and Nitin Joglekar. "A Survey of Technology Readiness Level Users." 26th Annual INCOSE International Symposium. Edinburgh, Scotland, UK, July 2016.

U.S. Department of Energy, Office of Management. Technology Readiness Assessment Guide. Washington, D.C., September 15, 2011.

U.S. Department of Energy, Office of Environmental Management. Technology Readiness Assessment (TRA)/Technology Maturation Plan (TMP) Process Implementation Guide. Washington, D.C.: March 2008.

York, Donald. “A Practical Guide to Determine the Readiness of Systems. Innovative Methods, Metrics and Tools for the Systems Engineer.” Tutorial, 29th Annual INCOSE International Symposium, Orlando, FL 20-25 July 2019.

National Aeronautics and Space Administration, “NASA Space Flight Program and Project Management Requirements” (NPR 7120.5E). Office of the Chief Engineer. Effective date: Aug 2012. Expiration date: Aug 2017).

National Aeronautics and Space Administration. “NASA Systems Engineering Handbook”, 2007.

National Aeronautics and Space Administration, Procedural Requirement (NPR) 7123.1B Appendix E (Technology Readiness Levels). Effective date: April 2013. Expiration date: Dec 2019.

Olechowski, A., S. Eppinger, and N. Joglekar. “Technology Readiness Levels at 40: A Study of the State-of-the-Art Use, Challenges, and Opportunities”. Portland International Conference on Management of Engineering and Technology. Management of the Technology Age. Aug 2015.

Sauser, Brian, Ryan Gove, Eric Forbes, and Jose Ramirez-Marquez. “Integration maturity metrics: Development of an integration readiness level”. Inf. Knowledge Systems Management, vol. 9. 2010.

Sauser, Brian, J. Ramirez-Marquez, R. Magnaye, and W. Tan. “A Systems Approach to Expanding the Technology Readiness Level within Defense Acquisition,” International Journal of Defense Acquisition Management. 2008.

Sauser, Brian, R. Gove, D. Verma, and J. E. Ramirez-Marquez. “From TRL to SRL: The Concept of Systems Readiness Levels”. Conference on Systems Engineering Research. 2006.

Systems Engineering, 27th Annual INCOSE International Symposium, Adelaide, Australia, July 2017.

Tomaschek, K., A. Olechowski, S. Eppinger, and N. Joglekar. "A Survey of Technology Readiness Level Users". INCOSE International Symposium. Edinburgh, UK. 2016.

United States. Department of Defense, "Technology Readiness Assessment (TRA) Guidance". Defense for Research and Engineering. 2011.

United States. Department of Defense. "Technology Readiness Assessment (TRA) Deskbook", Defense Research and Engineering. 2009.

United States. Department of Defense. "Technology Readiness Assessment (TRA) Deskbook", Defense for Science and Technology. 2005.

United States. Department of Defense. "Technology Readiness Assessment (TRA) Deskbook", Defense for Science and Technology. 2003.

United States. Department of Energy, "Technology Readiness Assessment Guide". Office of Management. September 2011.

United States. Department of Energy, "Technology Readiness Assessment (TRA)/Technology Maturation Plan (TMP) Process Implementation Guide". Office of Environmental Management. 2008.

York, D, et al., "Using Bayesian Networks to Validate Technology Readiness Assessments of Systems", Annual Conference on Systems Engineering Research, Mar 2017.

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