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Scientific Test and Analysis Techniques in Technology Readiness Assessments

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The STAT COE provides independent STAT consultation to designated acquisition programs and special projects to improve Test & Evaluation (T&E) rigor, effectiveness, & efficiency.

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Executive Summary

The Government Accountability Office's (GAO) Technology Readiness Assessment (TRA) Guide provides a strong framework for conducting credible, objective, reliable, and usable TRAs. While great detail is given to planning for assessment, decomposing a system into critical technologies to assess, and the reporting and using of assessment results, there is a lack of guidance on how to conduct and leverage tests to support TRAs. In this paper we discuss the application of Scientific Test and Analysis Techniques (STAT) to TRAs. We will also present STAT principles to guide a practitioner in making rigorous, credible assessments.

Keywords: Technology Readiness Assessment (TRA), STAT, STAT Process, test

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Introduction

The Government Accountability Office's (GAO) Technology Readiness Assessment Guide (GAO, 2020) provides a strong framework for conducting credible, objective, reliable, and usable Technology Readiness Assessments (TRAs). Great detail is given to planning for assessment, decomposing a system into critical technologies to assess, and the reporting and using of assessment results. However, there is a lack of guidance on how to conduct and leverage tests to support TRAs and the actual step of assessing the key technologies is not well defined. The evidence needed for an assessment are explained, but there is no guidance on how to actually apply that evidence. In this paper we discuss the application of Scientific Test and Analysis Techniques (STAT) to the TRA process. We will also present STAT principles to guide a practitioner in making rigorous, credible assessments and show how the steps for an effective assessment begin in the planning stages.

The remainder of this paper presents background on the TRA five-step process laid out by the GAO, provides a short summary of the STAT Process, and explains how STAT can be incorporated into the TRA process to facilitate effective assessments. In incorporating STAT into TRAs, we will emphasize relevant STAT principles to guide the assessment step.

Technology Readiness Assessment Background

A TRA is a process for evaluating the technological maturity of a system or set of systems in an acquisition program. The GAO guide to this process offers a systematic framework that emphasizes unbiased, evidence-based assessments. The result of a TRA is often communicated through the use of a Technology Readiness Level (TRLs), which is a measure of demonstrated system maturity (numbered 1-9). STAT inclusion in TRAs will be presented and understood in terms of how STAT fits into this framework. Elements the GAO framework and of TRLs are discussed in the following sections as requisite information for understanding the STAT concepts detailed in this paper.

GAO Framework

The GAO framework for TRAs presents a five-step assessment process to facilitate the use of credible, objective, reliable, and useful. These steps are

1. Prepare the TRA Plan and Identify the TRA Team
2. Identify the Critical Technologies (CTs)
3. Assess the CTs
4. Prepare the TRA Report
5. Use the TRA Report Findings

This process begins with planning and preparing well before an assessment is needed. Step 1, involves preparing a plan and building an assessment team. The goal of the TRA plan falls into one of two categories: 1.) Either the TRA is a comprehensive assessment of technology maturity to support a decision point (e.g., funding decision or an acquisition milestone), or 2.) The TRA is a knowledge-building TRA to assess maturity and progress during development. These two goals need to be clearly defined along with evaluation criteria for assessing test results, types of evidence needed for assessment, and program aspects such as schedule, resources, and funding. Once these various aspects are defined, the TRA team moves to the second step, Identifying CTs.

Step 2, Identifying CTs, involves decomposing a system or end product into smaller, more assessable levels and often relies on the Work Breakdown Structure (WBS) for this decomposition. The TRA team then works with subject matter experts (SMEs) to discriminate between the decomposed systems to select CTs. This discrimination is made with consideration for the assessment goals established in Step 1, and should result in a set of assessable technologies determined according to performance characteristics and the novelty/newness of the technology or use case. Selected CTs should not be technologies and subsystems that do not pose developmental risk, are already mature systems, or are not critical to the full systems operation.

Step 3, Assessing CTs, involves considering the available evidence to render a technology maturity decision for each critical technology, usually presented as a TRL rating. These assessments are carried out by evaluating evidence against general criteria defined in the TRL description. Evidence includes information such as test data and analytic reports. The assessments should be guided by the TRA purpose as defined in Step 1. For an objective, reliable, credible, and useful TRA, the CTs must be evaluated considering program purpose, requirements, key performance parameters, and capabilities.

Step 4, Prepare the TRA Report, involves drafting an account of the program description, evidence, findings, and conclusions from the prior steps. In addition to a logical defense of the assessment results, the TRA report must present any other information relevant to understanding technology maturity, developmental stage, or risk areas for the sake of guiding decision makers.

Step 5, Use the TRA Report Findings, involves using the TRA report for decision support. Actions in this step are focused around communicating with governing bodies, program managers, and technology developers about the technology readiness of a system in order to facilitate informed decision making. In addition to governance decisions, the TRA may be used to guide risk reduction efforts or inform on solutions to address immature technologies.

Conducted properly, the steps of the GAO framework enable technology maturity assessments that are credible, objective, reliable, and useful. A significant tool employed in many TRAs to enhance the usability of assessment results is the use of TRLs to concisely communicate technology maturity.

Technology Readiness Levels

A regular result of the TRA process, and the most common measure for communicating technological maturity of a system, is Technology Readiness Levels (TRLs). TRLs don't represent a single, measurable aspect of maturity. Rather, they are determined by a variety of characteristics that reflect technology progression through demonstrated capabilities. TRLs communicate technology maturity through a 9-level measure, as seen in Figure 1, which considers not only the level of performance demonstrated but also the forms of evidence used to support the TRL decision. Thus, higher TRLs require higher-fidelity information sources as proof of maturity.

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

Figure 1
Technology Readiness Levels (TRL)

Generally, TRLs are not determined as the result of a single, system-level assessment. TRLs are instead assigned to subsystems or components that represent technologies critical to the function and development of the full system, and they are generally determined as a result of a variety of assessments made over time as evidence is collected. When a TRL is presented for a higher-level system or subsystem than the level at which TRLs were determined, the resulting score is limited to the lowest TRL among its constituent technologies rather than an averaged value to reflect the criticality of the assessed pieces. When properly assessed, TRLs provide a quick and intuitive picture of the technology maturity of a system. One goal in incorporating STAT into TRAs is ensuring rigor is assigned to TRLs.

STAT Background

Scientific Test and Analysis Techniques (STAT) are deliberate, methodical procedures that seek to relate requirements to analysis with the goal of informing better decision making. To discuss the benefits of STAT in the TRA process, it is important to first understand the STAT Process

(Figure 2) (STAT COE, 2020). The STAT Process is not simply a method to select good test points. Rather, it is a methodical approach of planning, designing, executing, and analyzing a test plan. The goal in TRAs of evidence-based assessments to inform decisions is directly supported by the application of the STAT Process. The application of STAT in TRA planning and assessment will yield defensible technology maturity assessments and reduce the risk of negative cost and schedule impacts from inaccurate assessments.

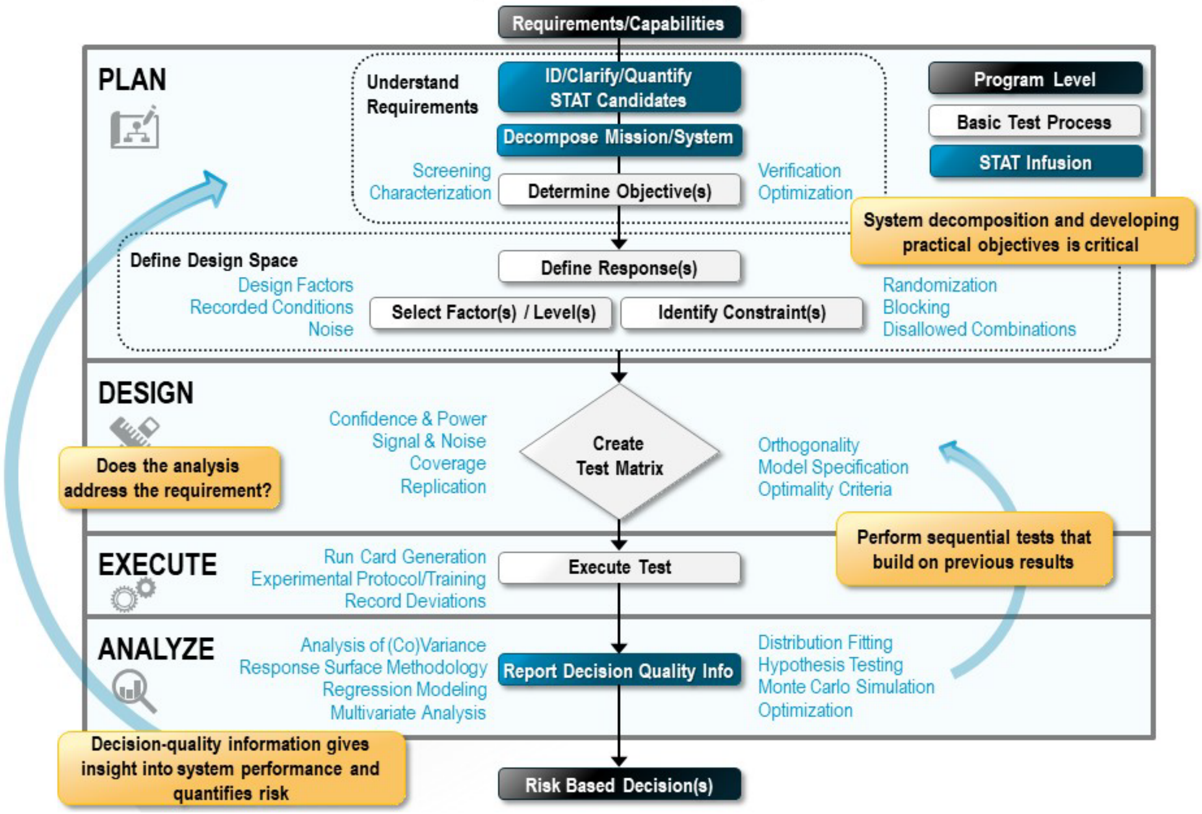

Figure 2

STAT in the Test & Evaluation Process Schematic

As systems become more complex, the application of STAT becomes increasingly necessary. The primary focus of the STAT Process is planning all phases of test, which begins well before data is ever gathered to be analyzed. Planning starts with identifying mission requirements that need a rigorous assessment approach and decomposing each requirement into smaller pieces which can be more directly evaluated through analytical methods. These decomposed mission requirements form the context through which all the following steps of the STAT Process are taken, culminating in the reporting of requirement-focused information to support decisions.

In planning, practitioners define test objectives and the test design space. This involves building clear, assessable definitions of evaluation measures, design factors and levels, and test constraints. Proper understanding of the test space and intended outcomes is necessary for success in the following phases.

In the design phase, test plans are built and optimized to maximize the information needed to achieve the test objectives outlined in planning. Many of the design considerations have already been clearly addressed in planning, and final considerations often revolve around tradeoffs between time or schedule cost, risk acceptance, and the desired level of fidelity needed from test results.

Most of the actions taken in the execution and analysis phases of the STAT Process have been decided during planning and design. Important considerations in these phases are how-to respond to issues experienced in testing or unexpected discoveries in test results. Many times, the STAT Process employs sequential designs allowing a return to planning and design after limited test execution to allow partial data to frame the next phases of testing. This results in a more efficient test plan. Analysis ends where it began with a focus on mission requirements by reporting test results in terms of mission requirements to support decision makers. This high level focus on mission requirements in reporting to support decisions is seen in both the TRA framework and the STAT process, leading to a strong synergy between the processes for providing reliable, actionable information.

STAT Inclusion

Much like the TRA framework, the STAT Process also encourages assembling a team of all stakeholders that includes, but is not limited to, test managers, engineers, SMEs, operators, and STAT experts. Both processes emphasize a top down approach where planning the objectives of the assessment can be derived directly from the requirements. Understanding the requirements and the progress toward meeting each requirement system maps directly to a TRL score. Systems with low TRLs are generally in the process of defining requirements and potential use cases and should utilize the mission decomposition laid out by the STAT Process to define quality requirements. Higher TRL systems have met a subset of the requirements laid out by the program or have shown significant evidence of progress toward meeting those requirements. Such programs can begin to utilize the STAT Process planning methods to define the test strategy that will be used to characterize the system based on its requirements.

The STAT phase of planning continues in the process of selecting CTs. In CT selection, the TRA team first defines program objectives, and decomposes the system into assessable parts to identify the components necessary to completing that objective. Here, the team would establish the assessment plan, and determine the performance criteria and evidence that is needed for a CT to meet a given TRL level or other established readiness goals.
In selecting the CTs, the TRA team should also begin the design phase of the STAT Process. Going through the design process prior to collecting data for assessment is critical to ensure credible, objective TRAs. If criteria are established after data collection, then the assessment results can be biased by program optimism about the current state of the system rather than by actual performance and technology progression measures.

In the step of assessing CTs, the TRA team concludes the design phase of the STAT Process and can be guided by the execution phase. In execution, data is collected and the assessment plan is followed for each CT, but the path to assess the CTs should already be established. The final phase of the STAT Process, analysis, concludes in rendering a TRL assessment for each CT and preparing the TRA report. The results and findings from CT assessments are considered, and presented in terms of their implications for system development and program risk. In each step of the TRA process, STAT provides guiding principles to support a rigorous TRA assessment.

Selecting Critical Technologies

The most critical step of the TRA process is selecting CTs and establishing their evaluation criteria. Selecting CTs begins with mission decomposition. This can be performed either by decomposing the system according to physical/software structure or by decomposing top-level system requirements into subtasks. Figure 3 shows an example of a mission decomposition into subtasks.

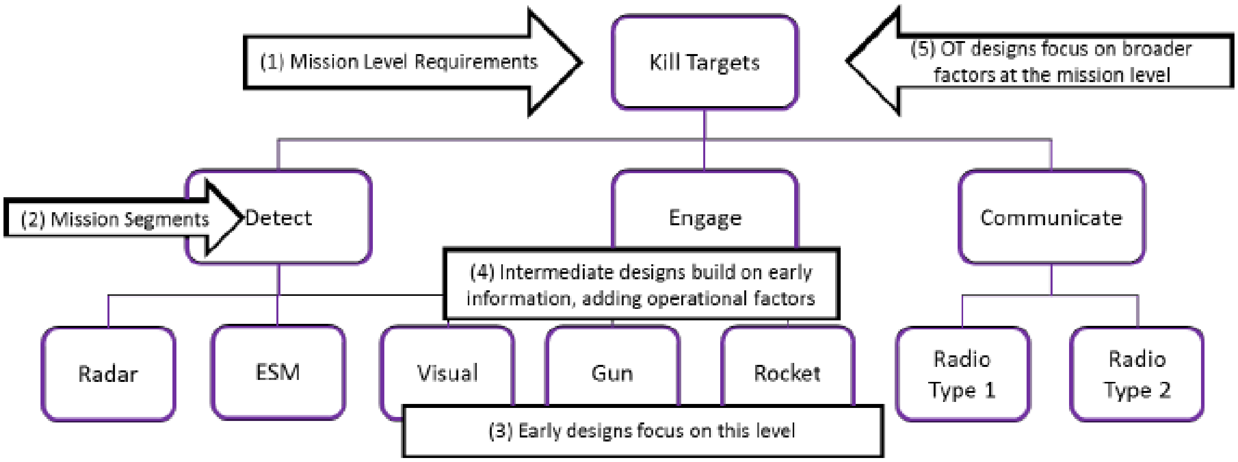

Figure 3
Mission Decomposition Example

At higher levels, tasks or components may be characterized by complex functions that lack clear evaluation metrics. At the lower level, tasks or components can often be defined simply with an individual function relating to overall mission performance. This is the level where CTs should be evaluated, resulting in clearly assessable tasks. After performing the decomposition, selection of critical technologies is very similar to selecting STAT candidates for testing. Not all aspects of a system will need to be tested using STAT and the STAT candidates can be identified using Figure 4 as a guide. These same STAT candidates are likely to be the CTs.

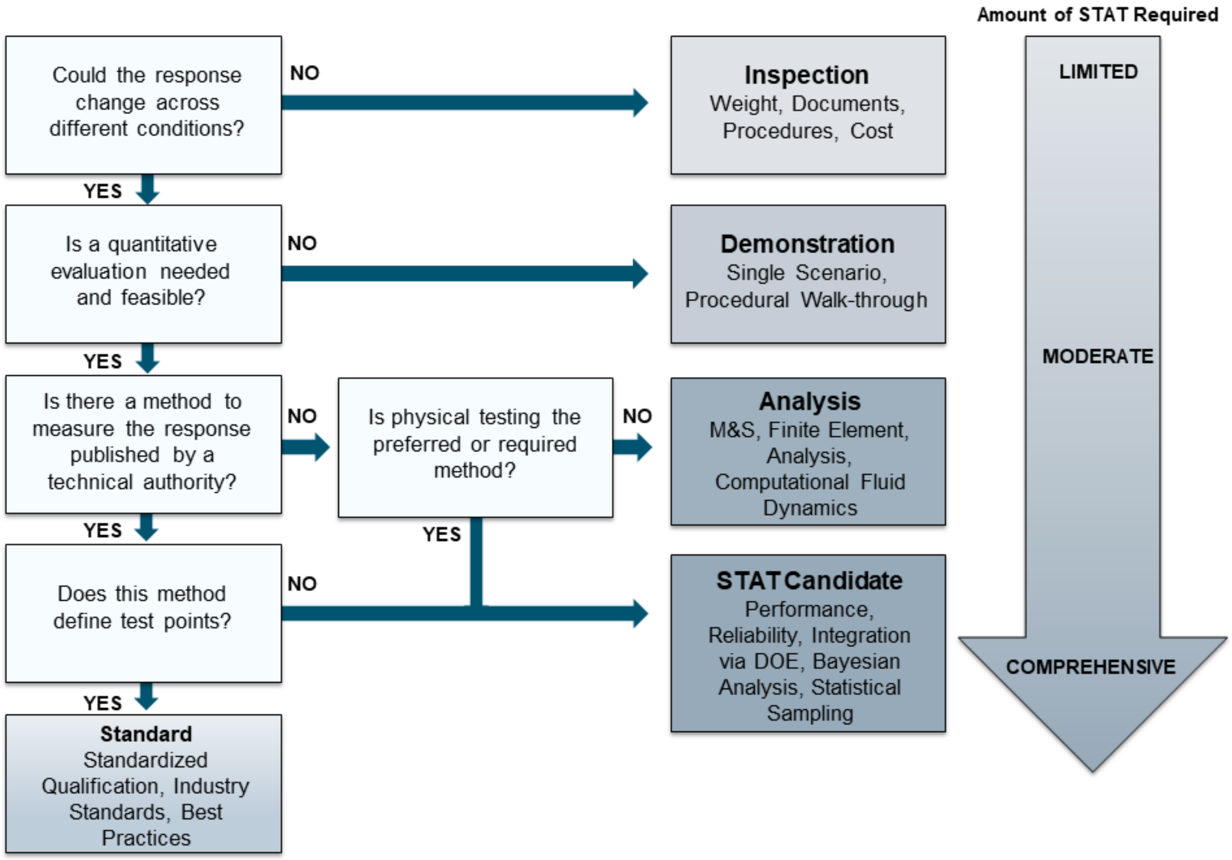

Figure 4
Steps to Determine Which Requirements Should be Verified Using STAT

Critical questions for selecting CTs:

1. Does the components function relate to top-level mission requirements?
2. Is there any risk in the development, upgrade, or integration of the component that needs to be quantified?
3. Is there a performance metric for the component that clearly impacts the system's ability to meet mission requirements?
4. Could the performance of the component vary across different conditions or as technology reaches further maturity?
5. Is a quantitative evaluation of the components performance needed to understand the system's ability to meet mission requirements?

If the answer to all of these questions is yes, it suggests that the component is a CT for the system. If the answer to any of these questions are no, it could imply that the technology is not a CT, but it might also suggest that a higher or lower decomposition level needs to be considered. An example may be a functional requirement of a communication system or subsystem to be able to receive and send data through the Link 16 tactical data link network. Such a function has a binary definition, either meeting the requirement of Link 16 capability or not, with no assessable measure for progress toward meeting mission requirements. For the sake of assessing technology maturity, it may be prudent to assess lower-level components with measurable progress towards mission readiness.

Assessing Critical Technologies

After selecting CTs, assessment criteria need to be established for the evaluation of technology maturity for each system. To guide the evaluation criteria, the TRA team may consider the known TRL of a component prior to assessment. This prior TRL may come from a previously conducted assessment, or the TRA team may conduct a preliminary assessment to determine the TRL of a component at the beginning of development. After determining the prior state of a system, the TRA team consults with SMEs, and reviews performance objectives, program schedule, and history of analogous systems to determine the evidence needed to show that the higher TRLs have been reached. Establishing assessment criteria should be done prior to any review of the current state of the CT to be evaluated in order to ensure an objective TRA. Furthermore, the assessment criteria should be defined using comparisons to development patterns seen in analogous systems or technologies to ensure credible and reliable TRAs.

The STAT Process is valuable for assessing critical technologies and can be applied to any testable system or component. The Process is designed to produce an efficient, effective, and defensible test strategy to assess requirements. This is applicable at any stage of development to characterize performance. In defining performance expectations for each TRA level, a best practice is to ensure that performance criteria are clearly defined. Montgomery defines a clearly defined objective as one which is specific, unbiased, measurable, and of practical consequence (S.U.M.O) (Montgomery, 2021).

Specific

In order to be specific, performance criteria must be stated clearly and unambiguously so that a review of performance data will leave no questions as to whether the criteria are met. The answers to the below questions must be established prior to reviewing assessment materials.

- Does expected performance need to be achievable in all domains of the mission space, under standard operating conditions, or only under optimal conditions?
- Do the criteria represent performance standards which a component must always surpass, surpass on average, surpass a given proportion of the time, or simply be capable of achieving?
- Is it sufficient to achieve performance expectations as an isolated component, or must performance be demonstrated in an integrated system?
- Does falling short of technology maturity expectations demand remedial measures, or is there a lower performance level threshold for when such measures will be needed?

Unbiased

In order to be unbiased, assessment criteria should be reviewed and agreed upon by all stakeholders. Program managers, engineers, technology developers, system users, and SMEs from outside the program should all have representative parties who review and agree on the technology maturity expectations for a critical technology at each TRL level. Much of the consideration for unbiased TRAs is performed in Step 1 of the GAO framework, but the selection of CTs allows a point of further review to ensure technology experts have been identified for each technology under review.

Measurable

To be measurable, it is important that an evaluation criterion is not only based around a quantifiable response, but that the measured response clearly represent the components ability to satisfy mission requirements. The TRA team must consider what ranges of the response would satisfy mission need, and to what level of accuracy the response can be measured.

Where possible, criteria should be built around finer detail measurements such as how far from target performance a system achieves on average (which measures continuous data about individual system events) instead of how often system performance is within an acceptable range (which measures binary information about individual system events). For TRLs needing more than a demonstration, the TRA team should determine the statistical measures of confidence required to establish that the criteria have been met.

Of Practical Consequence

To be of practical consequence, assessment criteria must all be tied to top-level requirements, and whether a CT meets the required criteria should practically impact the system's ability to achieve those top level requirements. In other words, failing to meet a certain requirement should have an impact on the TRL. Furthermore, assessment criteria should be established with test schedules in mind to ensure that the needed evidence will be achievable.

After assessment criteria is established the TRA team can begin collecting evidence of technology maturity. The evidence collected should be current, and consistent with the TRL level that technology developers seek to prove, as shown in Figure 1. The method to collect this data should utilize the STAT Process of proper test planning and execution. While the assessment plan has been established, adjustments may need to be made where the plan proves unrealistic. Altered test plans, limited budgets, or unexpected development events can all make the planned assessments strategy implausible or impractical. In these cases, the TRA team may reassess the type of evidences they need to support a CT evaluation, or the amount of evidence needed to support a CT evaluation. The iterative nature of the STAT Process allows for changes like this to be implemented by returning to previous steps in the Process to reassess where changes are needed. In exceptional cases, the TRA team may even conclude that there is insufficient evidence to render a decision, following guidance laid out in the GAO Technology Readiness Assessment Guide. In cases where the assessment criteria are adjusted, the TRA team must ensure that new criteria are not built to reflect current observed performance. Performance thresholds shouldn't be moved until the TRA process begins again to support a new assessment.

With well-established criteria, there should be little room for interpretation of evidence while assessing the CTs. Shortcomings in performance as well as any changes that were necessary to assessment criteria should be recorded as risk areas for the next step of the TRA process. If any disagreements arise regarding the readiness levels of a CT, this should also be recorded as an assessment risk, clearly stating the assessment criteria, the measured performance, and the basis of the disagreement.

Preparing the TRA report

The preparation of the TRA report is the final point of STAT inclusion for the TRA process. Most analysis decisions have been made or have been planned for during the previous steps. In recording the results of those decisions, the TRA team must go back to requirements. Assessment criteria, evidence used in assessment, critical technology selections, development risks, and changes to the TRA plan as it was conducted must all be recorded and framed in terms of implications for top-level system requirements. Statistical analysis should be included where appropriate to show the current level of performance in a system. In preparing the report, TRL levels may be assigned to higher-level components than the level at which the system was assessed in order to assist communication of technology maturity. However, the higher-level component's TRL can be no higher than the lowest TRL among its sub-components. As a final STAT consideration, the TRA team should record any findings relevant to planning for any future TRAs. Recording all these elements with top-level system requirements in mind will ensure the report is a highly useable product for informing acquisition decisions.

Conclusion

TRAs commonly inform acquisition strategies, and are considered during decisional milestones throughout the technology development, product development, and production of major acquisition systems. The weight that TRAs carry in shaping the understanding of technology maturity demands that full effort be put towards ensuring that TRA reports are credible, objective, reliable, and useful. The rigorous approaches outlined in the STAT Process naturally compliment the TRA process well. The STAT Process ensures that TRA results are credible and objective through emphasis on sound scientific and mathematical principles and that results are reliable and useful through emphasis on an approach focused on mission requirements. Adoption of STAT in TRAs enables decision makers to make the best use of available information to reduce risk in major acquisition decisions.

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Appendix

DOD TRL Definitions

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.

Table 8: DOD Software Technology Readiness Levels (2009)	**Definition**	**Description**
1	Basic principles observed and reported.	Lowest level of software technology readiness. A new domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms.
2	Technology concept and/or application formulated.	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies using synthetic data.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties and analytical predictions using non-integrated software components and partially representative data.
4	Module and/or subsystem validation in a laboratory environment (i.e., software prototype development environment).	Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy element as appropriate. Prototypes developed to demonstrate different aspects of eventual system.
5	Module and/or subsystem validation in a relevant environment.	Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment.
6	Module and/or subsystem validation in a relevant end-to-end environment.	Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype

		implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems.
7	System prototype demonstration in an operational, high-fidelity environment.	Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations, where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.
8	Actual system completed and mission qualified through test and demonstration in an operational environment.	Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality tested in simulated and operational scenarios.
9	Actual system proven through successful mission-proven operational capabilities.	Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system.