A SUPPLEMENTAL REPORTING TOOL FOR ASSESSING TECHNOLOGY READINESS

Michael P. Thompson
Boeing (Retired)
Tacoma, WA/USA

ABSTRACT

In current practice, technology maturity is generally measured in terms of Technology Readiness Level (TRL). Technology Readiness Levels range from Level 1 (Basic Principles Observed and Reported) up to Level 9 (Actual System Flight Proven). TR Levels are established by answering multiple generic questions to assess technology maturity at each Level. The TR Level definitions are also generic, and the methodology implicitly assumes that levels are worked consecutively (i.e., that all Level 1 work is completed before beginning Level 2, and so on). These characteristics create limitations in terms of fully and accurately illustrating actual technical progress. This paper proposes a supplemental reporting tool for technology maturity assessment, utilizing customizable scaling levels to reflect actual project milestones, along with a simple binary (Met/Not Met) status for each requirement at each scaling level. Full technology development status can thus be summarized with a single-page chart using simple color-coded blocks to show progress at meeting all requirements for all scaling levels up to final production implementation.

1. INTRODUCTION

In any large organization which develops new technologies, there is a need for "snapshot" project status reviews, to enable senior management to quickly assess and compare the maturity of all projects within the organization's portfolio, thus enabling decisions regarding priority, funding, and implementation scheduling for all technologies under development. The most common methodology for these snapshot assessments is the Technology Readiness Assessment concept originally developed by NASA in the 1980's, and since adopted by the Department of Defense, other governmental organizations, and many private companies [1]. Each project is assessed against multiple criteria and its maturity is reported as a "Technology Readiness Level" (TRL), with TRL1 being least mature ("Basic Principles Observed and Reported"), and TRL9 representing a fully mature technology ("Actual System Flight Proven").

The purpose of this paper is to propose a supplemental reporting tool for measuring technology readiness. This new reporting tool is tied to the specific test parts and demonstration articles required to prove out new material and fabrication process technologies and applications. It can be reviewed at a glance to provide substantially more project information than just a numerical TR Level, and reflect actual project development more accurately than the TRA methodology. This new reporting methodology is not a replacement for TRLs – it is intended to be an additional supplement to aid senior management in decision-making.

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The scope of this paper is limited, and addresses fabrication of aerospace structural composite parts and assemblies (the author's area of technical experience). However, it is anticipated that many of the principles described herein would also be applicable to metallic structure and components for non-aerospace applications. Much of the literature regarding Technology Readiness Assessment considers development of complete aircraft and space vehicles, which incorporate not only new materials and fabrication processes, but also new mechanical, electrical, avionics, software, control, and integration systems. Projects at that scale are beyond the scope of this paper.

In typical practice, aerospace developmental projects are not targeted at generic technologies (e.g., "prove oven cure works" or "prove this prepreg works" or "prove this forming process works"). Most projects are targeted at specific applications which already have a scheduled production insertion date (e.g., "prove that oven cure can be used to successfully fabricate *this specific new wing spar with all these specific design features,* and be production-ready in two years.") Thus "technology development" (for oven cure in this case) is completely intertwined with application development of the new spar design. It is these types of composite part developmental projects for which this new reporting tool is targeted.

2. CREATING AND EXECUTING THE DEVELOPMENTAL PROGRAM

2.1 The Building Block Approach to Creating the Test/Evaluation Program

The first step in developing a new composite part technology is creation of the test/evaluation program. This test program not only has to generate data which demonstrate acceptable part quality and mechanical strength under all appropriate loading and environmental conditions, its manufacturability evaluations must demonstrate consistency in part quality and compatibility with tooling and other required processes.

The aerospace industry has adopted the "Building Block" approach to designing such test programs for structural part development. Figure 1 illustrates the key features and scaling level descriptions used in the Building Block approach [2].

FAA Advisory Circular AC20-107B [3], dated 9/8/2009, which addresses the subject of showing compliance to FAA regulations for composite aircraft structure, includes a good summary of the rationale and benefits of the Building Block approach: "The strength of the composite structure should be reliably established, incrementally, through a program of analysis and a series of tests conducted using specimens of varying levels of complexity. Often referred to in industry as the 'Building Block' approach, these tests and analyses at the coupon, element, detail, and subcomponent levels can be used to address the issues of variability, environment, structural discontinuity (e.g., joints, cut-outs or other stress risers), damage, manufacturing defects, and design or process-specific details. Typically, testing progresses from simple specimens to more complex elements and details over time. This approach allows the data collected for sufficient analysis correlation and the necessary replicates to quantify variations occurring at the larger structural scales to be economically obtained. The lessons learned from initial tests also help avoid early failures in more complex full scale tests, which are more costly to conduct and often occur later in a certification program schedule."

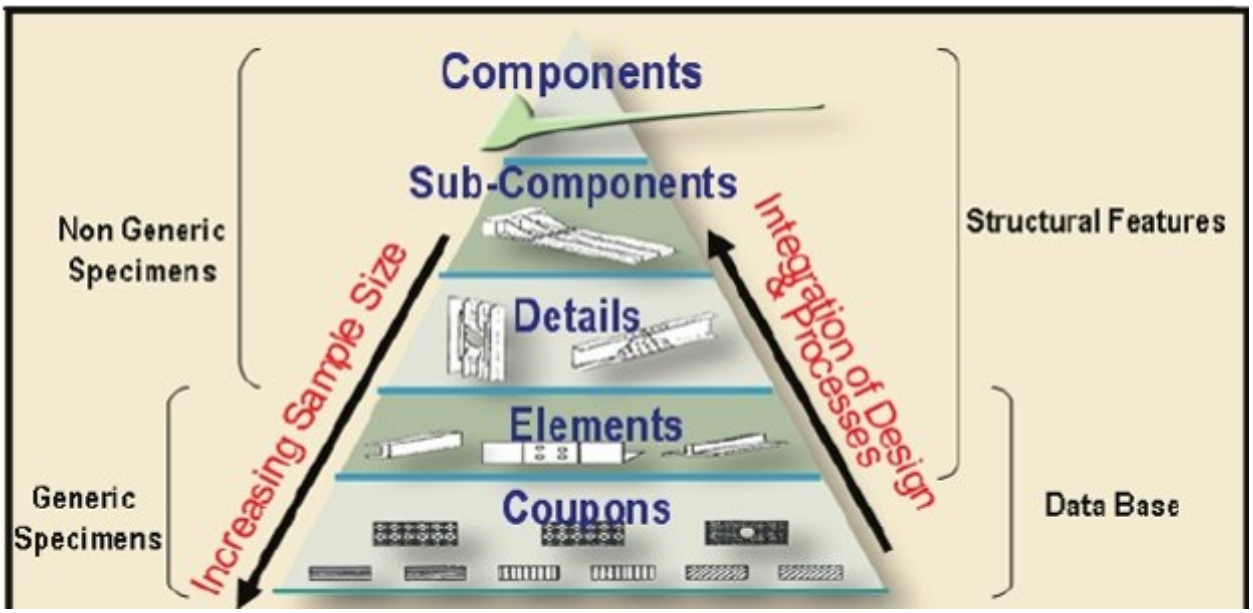


Figure 1. Example Building Block Diagram For Technology Development Projects

Note that the Building Block approach as illustrated in Figure 1 provides only generic scaling levels (Coupon/Element/Detail/Subcomponent/Component) in its guidelines and principles for designing structural test programs. For the project-specific test program, Structures Engineering and other Engineering groups utilize these principles to design the necessary customized hardware articles and test requirements to validate all aspects of the technology development effort. The project-specific test program might include variations on the Building Block scaling levels, or include individual test articles which address more than one of the Building Block levels, and therefore might not neatly fall into one of the five categories shown in Figure 1.

Therefore, for clarity purposes within this paper, the scaling levels associated with the project-specific test parts, demonstration articles, and process compatibility trials shall be collectively designated "Test Article Scaling Levels" (TASLs), to differentiate them from the five Building Block scaling levels and the nine Technology Readiness Assessment scaling levels (TRLs).

Typically, the lowest Test Article Scaling Level (TASL1) comprises one or more flat panel configurations which must meet specific mechanical requirements. The next level up in terms of of size or complexity (TASL2) includes one or more contoured panels which might incorporate convex or concave radii, thick and thin areas, ply drops, and other basic part features. Intermediate TASLs would include demonstration articles to address the specific part features and process needs – perhaps contour joggles or prepreg formability capability or automated tape laydown or inspectability of specific part geometries, and so on. Higher TASLs would address increased part size and thickness and structural integration. The test articles are specifically designed so that collectively, they validate all end item production part requirements. Each test part has its own defined list of requirements which are either Met or Not Met – there is very little subjectivity or ambiguity in these judgments. Success is not achieved until 100% of the defined requirements are Met for all test parts and demonstration articles.

2.2 The Project Engineer and Execution of the Test Program

Once Engineering has established the test program and requirements for each test part, the project engineer takes responsibility for project execution. With even the best-designed test program, there are countless details which must be addressed and process issues to resolve to demonstrate that all test article requirements are met. The project engineer is constrained by test article designs and requirements, but there is considerable latitude for creativity in identifying successful manufacturing processes. The project engineer also must determine how to sequence tasks to optimize overall project progress.

2.2.1 Process Robustness and Specific Part Features

In trying to assess overall technology maturity (or simply asking whether a process works or not), a common reality in composites technology development is that for the vast majority of the part in question, the manufacturing process is fully robust, but the small remaining fraction of the part contains features where all the technology problems occur. Instead of one technology challenge for the entire part, the project becomes divided into several feature-specific process development mini-projects. These problem areas might be as small as a few square inches, but these types of challenges can be intractable and threaten success for the entire project. Such challenges might include exotherms during cure for thick laminate areas, inability to achieve proper consolidation pressure in high contour areas or joggles, excessive entrained air or moisture causing porosity within composite laminate ply drop areas or bondlines, localized ply wrinkling, and so on. It occasionally happens that expensive large-scale process revisions must be developed to accommodate such problem areas. These sorts of issues are a major concern for the project engineer.

2.2.2 Risks of Rigid Adherence to the Implied Building Block Sequence for Development

The Building Block approach as illustrated in Figure 1 carries the implicit assumption that small coupon trials should be completed first to understand small-scale phenomena, before progressing to element trials and then details and so on, up to full-scale components evaluated last. In the field of structural composites, however, strict adherence to this approach may not always be best.

Chemistry and physics obviously do not change from the small-scale to the large-scale. But composites history is littered with costly examples of our imperfect understanding of the physics of composites processing and cure in regard to scaling effects. Such problems typically include resin rich or poor areas, porosity/void formation, delaminations, ply wrinkling, and warpage. A process that consistently produces acceptable laminate for small-scale parts can fail dramatically for large-scale parts. There are currently many limitations to our understanding of what is happening during cure inside a large complex composite part at specific part feature locations regarding resin flow, resin polymerization, resin pressure, and fiber movement. The point here is that for technology upgrade efforts involving new materials, process parameters, or design concepts, no matter how many small parts I have successfully fabricated, even with simulated part features, I may be wrong in assuming that I can now safely scale up to full size. For a new composite material or an innovative cure cycle, we might not know what will happen with a 15-meter (50-foot) configured part until we make one. In such a case, where large-scale processing problems are not identified until late in the project, the cost and effort required to modify process parameters and redo testing required for validation can be exorbitant.

All of this serves as a warning regarding rigid adherence to the sequential nature of the Building Block Approach and the TRA methodology. In structural composites applications, a process engineer who relies exclusively on small test coupons and TRL3-scale "proof of concept" demonstration articles to establish the process parameters for large parts is asking for trouble. The project engineer is well served to fabricate simulated larger parts early in the project, to identify processing issues which might not otherwise appear until prototype part validation (TRL6 or TRL7) is underway. Likewise, demonstration articles with anticipated part features should be fabricated early in the project, to identify which features are likely to cause defects. Final designs for production tooling and parts do not have to be complete to make these demonstration articles. Approximations are usually sufficient, and are certainly better than strict reliance on the process knowledge gleaned from test coupons and small demonstration articles.

In a large complex composites development project, therefore, it is entirely likely that fabrication and testing of both small-scale and selected large-scale demonstration articles will be occurring simultaneously, as will be mid-sized test articles to validate processing for specific part features.

3. ASSESSING TECHNOLOGY READINESS

A large organization may have tens or hundreds of projects in work, and senior management doesn't have time to review voluminous reports on every project when making decisions regarding technology implementation, prioritization, scheduling, planning, and funding. A reporting tool is therefore needed, so that project engineers can provide management with high-level "at-a-glance" status on each technology development effort. Management can then review all these reports to assess the overall portfolio of projects and make appropriate plans for the future.

The generally accepted industry standard for this "snapshot assessment" is the Technology Readiness Assessment (TRA) methodology first developed by NASA in the 1980's. The TRA methodology establishes nine Levels of technology maturity ranked by "Technology Readiness Level" (TRL). The criteria to meet each TR Level are shown in the familiar NASA "Thermometer" diagram shown in Figure 2. Technology maturity at any given time is simply reported to management by Level ranking.

The Technology Readiness Levels are generic. The same nine TR Levels are used for any technology development effort. It doesn't matter if the required technology development involves material upgrades, process improvement, tooling or equipment changes, or new structural designs, it is assumed that the same evaluation methodology can be applied across the board.

The TRA methodology for estimating technology maturity assigns a single Technology Readiness Level to the entire project. There is no consideration that certain aspects of the project might be more advanced than others. For a "TRL4" project, this creates the implicit assumption that every aspect of the project has been successfully completed up to "component validation in a laboratory environment" (per Figure 2), and that work is now progressing to achieve TRL5 ("component validation in a relevant environment"). In more general terms, the TRL approach implies that the project engineer works through a set of TRL3 tasks, then a set of TRL4 tasks, then TRL5, and so on, sequentially progressing through each Level in increasing order.

Engineers and managers understand that workflow is not that orderly, but this is how progress through the TR Levels is communicated.

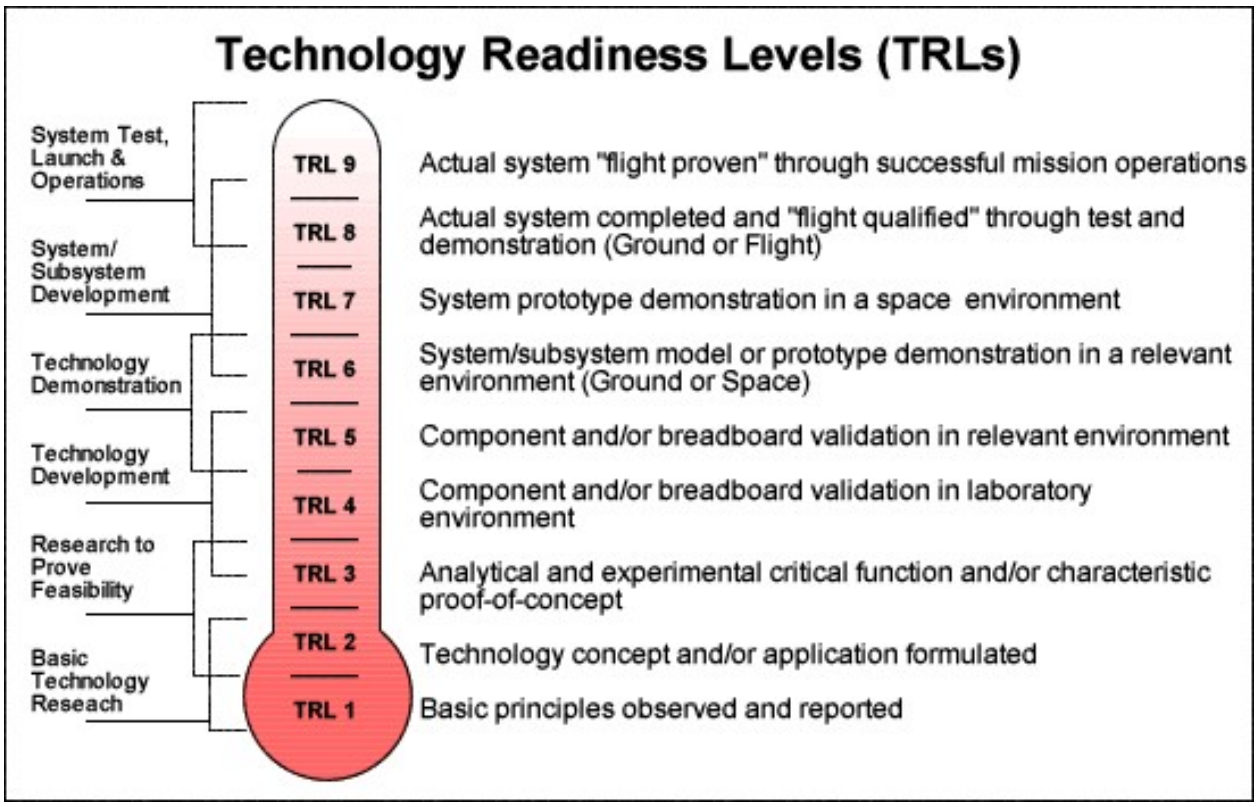


Figure 2. NASA "Thermometer" Diagram Defining the Nine Technology Readiness Levels

3.1 Assessing Maturity and Assigning the Appropriate Technology Readiness Level

As a technology development project progresses, it moves sequentially through the successive TRLs via periodic reviews. The common practice for upgrading TRL status is through answering a series of questions specific to each Technology Readiness Level which interrogate the various aspects of the project for technology maturity. Examples of such questions can be found in the Air Force Research Laboratory (AFRL) "Technology Readiness Calculator" [4], and the Department of Energy's process guide for technology readiness assessment [5]. Other organizations may have their own lists of questions. The questions are structured to have Yes/No answers, but the AFRL methodology also allows for a "percent complete" response to each question. The lists of questions are typically rather lengthy. For example, in transitioning from TRL4 to TRL5, the AFRL Calculator asks 47 different questions, and the Department of Energy process guide asks 34. Ideally, all answers must be "Yes" to advance to the next TR Level.

Similarly to the Technology Readiness Levels themselves, the lists of questions used for level assessment are generic. They are not customized to the project in question. No matter what technology is being developed, the same questions are asked.

3.2 Benefits and Limitations of the TRA Methodology

This generic nature provides the TRA methodology with some attractive features. The simple "TRL4" or "TRL5" status (for example) provides senior managers with an instantly understandable measure of technology maturity. In hearing that one project has reached TRL7 while another is at TRL5, managers have a clear idea of which is closer to production implementation. This also promotes standardization of assessments across the full portfolio of projects. Another positive feature of TRA methodology is that answering all the detail questions forces the project engineer to thoroughly consider all aspects of the development effort.

There are, however, significant limitations to the TRL approach if used alone. Simply stating "this project is at TRL5" provides very limited information. There is no accounting for differences in project complexity or difficulty. There is a certain ambiguity in how to report status for parts where all areas of the part meet requirements except for one or two small design features. Additionally, the TRL status only reflects the Level for which *all* requirements have been met, and does not provide visibility of early work that has been done at higher or more complex developmental levels to mitigate risk.

Furthermore, properly assessing technology maturity via the TRA methodology is not straightforward. Thousands of pages of documents from multiple government agencies provide additional guidance and address challenges with TRA methodology. NASA, in fact, conducted multiple in-depth studies over a recent 5-year period to review TRA methodology and recommend upgrades, culminating in a 2016 report entitled "Final Report of the NASA Technology Readiness Assessment (TRA) Study Team" [6]. In this report, NASA made numerous improvement recommendations, including consolidation of paperwork, clarification of terminology, additional guidance information for TRA evaluations, and increased training.

The NASA report also emphasized the fact that reporting only the TR Level for a given project is not sufficient. The report reinforced the importance of supplementing the TRL assessment by using the "Advancement Degree of Difficulty" (AD^2) methodology for risk assessment of upcoming challenges required to move from the current TR Level to the level required for production implementation [7]. With the AD^2 tool, each aspect of the project is rated in terms of likelihood of success for full production implementation. There are nine AD^2 risk levels, with Risk Level 1 signifying minimal risk and Risk Level 9 signifying the need for completely original research. The AD^2 method also correlates the likelihood of failure with the consequence of failure to assess full perfomance/cost/schedule potential impact to the project. As with TR Levels, assigning the proper AD^2 risk level is not straightforward. One document showing the questions which must be addressed shows 9 questions to be answered for Design and Analysis, 20 questions for Manufacturing, 9 questions for Operations, and 13 questions for Test & Evaluation [8]. Since these questions involve estimation of solution probabilities for as-yet undeveloped technology, they are by nature approximations based on the personal experience of the reviewer(s). Note that for a composites fabrication project that involves a large complex part with multiple specific design features, each of which may require specific process solutions, these questions might have to be asked for every specific design feature.

4. CREATING A MORE SUBSTANTIVE ASSESSMENT REPORT

A more informative TRA supplemental report would incorporate the following features:

- Present overall project status in an easily understood one-page format for quick review
- Reflect the actual customized scaling level test articles to be fabricated
- Denote requirement progress with binary "Met/Not Met" status
- Reflect work being done on multiple scaling levels simultaneously
- Include flexibility for an evolving project to add, modify, or group requirements

Figure 3 illustrates a sample template to illustrate the features of this supplemental "customized binary" technology development snapshot report. This type of report is easily produced using commercially available spreadsheet software.

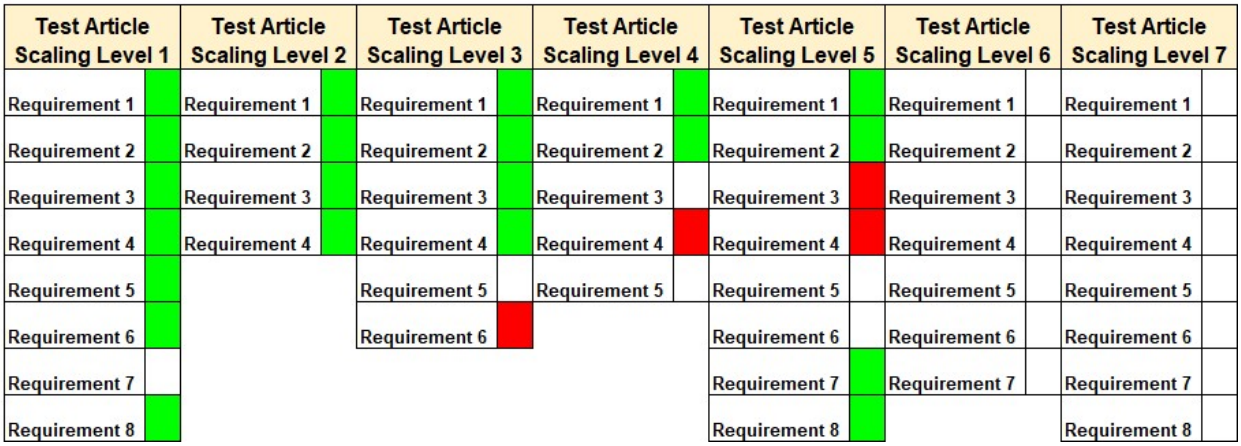


Figure 3. Template Example of New Supplemental Technology Development Reporting Tool

As described previously, the Test Article Scaling Levels (TASLs) are based on the specific physical demonstration articles which must be fabricated, and are therefore customized to the application in question. In an actual report, they can be titled to provide additional descriptive information. The various Engineering groups may assign more or less TASLs than the nine Levels used in the TRA methodology.

Requirements which have been met are shown in green. Requirements not yet tested are shown as blank squares. Failed tests are of particular significance in terms of project risk, and are shown in red to draw management attention. The red squares reflect that some sort of fix is required to achieve project success. There is little to no ambiguity or judgment required regarding test status for any requirement at any Test Article Scaling Level.

The report illustrates work performed to date at all scaling levels. It may be that one or more tests at TASL1 have been delayed and are not yet complete. At the same time, larger test articles may have already been fabricated and some requirements already demonstrated. This report format provides this type of multi-Level visibility.

The report can be modified as the project evolves to add TASLs or modify requirements as needed. As a project progresses, it is very common to find that additional test articles are required to demonstrate full technology maturity due to previously unforeseen issues, or that additional requirements must be created. In addition, as the project moves closer to success,

previously met requirements can be grouped for brevity, allowing greater focus on unresolved issues for the benefit of management in decision-making.

4.1 Hypothetical Project for Detailed Illustration

A hypothetical project involving development of a new composite airplane wing spar can be used to illustrate how the new reporting tool functions. This spar will incorporate a new composite material requiring validation of a suitable cure process, and the design will include radius areas requiring automated multi-ply forming processes, severe ply drop regions to transition from thick to thin laminate areas, contour features with joggles and a significant twist section, and attachment areas utilizing hard bagside caul tooling to maintain surface flatness.

The basic technology milestones for such a project would include the following:

- The proposed cure cycle produces acceptable quality laminate (low porosity, voids, etc.)
- Basic composite mechanical properties at coupon level are acceptable
- Properties after impact, fatigue, and environmental exposure are acceptable
- Large-scale mechanical tests are acceptable
- Automated tape laying process is compatible with new material
- Inspection processes are compatible with the new material
- Drill/Trim/Assembly processes are compatible with new material
- Acceptable repair methods are available
- Large-scale parts can be fabricated and meet cure cycle ramp rate requirements
- ALL part features can be fabricated to reliably meet acceptable quality levels:
  - Thick and thin areas and ply drop transitions
  - Joggle areas
  - Convex and concave radii and spar twist sections
  - Attachment areas under hard caul tooling

Figure 4 illustrates the new supplemental technology development status report for this hypothetical spar development project. This illustration assumes roughly a midway point in the overall technology development project (i.e., TRL4 or TRL5).

For this hypothetical project, Engineering has selected seven Test Article Scaling Levels for the test parts required to demonstrate sufficient technology maturity to put this spar into production:

- TASL1 is a set of flat panels of various configurations which must meet certain quality requirements and several mechanical strength requirements.
- TASL2 is a set of small contoured panels to demonstrate capability to fabricate radius areas and ply drop areas, as well as validate that inspection processes are compatible.
- TASL3 comprises larger sub-scale test parts fabricated to separately address specific design features. Level 3A is a test article to evaluate processing for a simulation of features common to the thick end of the part. The Level 3B article addresses the twist section of the spar, and Level 3C addresses attach points with bagside hard cauls.
- TASL4 is a large-sized simulated spar demonstration article. This test article is fabricated early in the development process. In addition to large size, it incorporates expected features in the final part. Although expensive in comparison to the smaller test

articles, this demonstration is used as an "early warning sign" to identify potential scaling issues before final designs, tooling, and process parameters are established.

- TASL5 is a large-scale structural test article.
- TASL6 is a full-scale final configured stand-alone spar.
- TASL7 is the fully assembled spar as mounted on an aircraft wing.

The Figure 4 report illustrates technology development at all scaling levels. In this example, note that the fatigue test under TASL1 is not yet complete, since fatigue cycling may require many months. The project engineer will not stop other work while waiting for the Fatigue test, so multiple tasks for higher TASLs have proceeded and many of the requirements for these more advanced test articles have already been met satisfactorily. However, under strict TRL definitions, one could argue that this project must be rated a TRL2, because until final Fatigue results are available, there is no guarantee that even coupon level performance has been fully validated. By itself, this would be a misleading rating.

The blank squares in the report illustrate the requirements for which testing has not yet been performed, and the red squares indicate the critical issues where demonstration articles failed to meet test requirements.

This one-page report can be reviewed at a glance, another critical characteristic for senior managers who must review and compare dozens of projects for decision-making purposes. With one look at this chart, management can understand what has been done, what has not been done, and what tests have failed, for all demonstration articles and Test Article Scaling Levels. This is substantially more information than is provided simply by stating the TR Level.

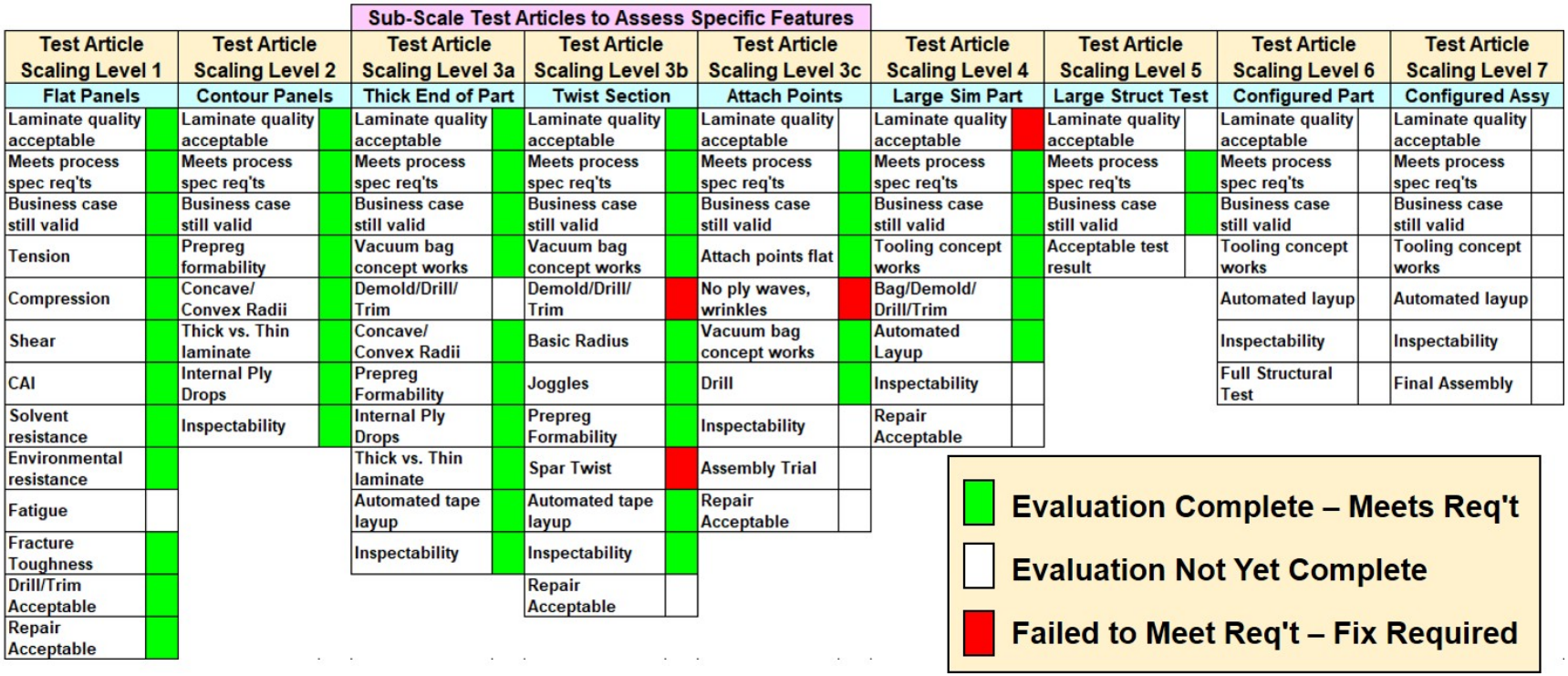


Figure 4. Supplemental Technology Development Status Report For Hypothetical Spar Project

It is recognized that some projects might have a large number of required test articles and/or very long lists of requirements and all this information might not easily fit onto a single-page report. This is especially likely as a project matures and unforeseen challenges occur, requiring additional test demonstration articles and/or new requirements. Adding a second page to the report is one option to address such cases. Another option is to reformat the blocks in the report to group categories for previously met requirements. In terms of management attention, detailed review of previously met requirements is much less important than attention to work not yet completed or especially failed tests. As a project matures, the report can evolve to maintain the emphasis on remaining challenges.

Figure 5 illustrates key columns for the technology development status report for the same spar development project, at a later date than what was shown above in Figure 4. Note that for some columns, previously met requirements are grouped into a single block and described as "All Requirements Met" or "Base Requirements Met." This allows greater emphasis on the cells shown with red text. These are the updated blocks which show that success has been achieved for many of the unmet requirements from Figure 4 (note that most are green), as well as provide visibility of the two new demonstration articles and several new requirements added since the Figure 4 report was generated. The report also highlights a new failed test, representing that manufacturing continues to struggle with achieving properly consolidated wrinkle-free laminate at joggle areas of the twist section of the spar. As a companion to the primary TRL status level, this report provides much greater specificity to management regarding realistic status of the overall project and identification of remaining challenges to production implementation.

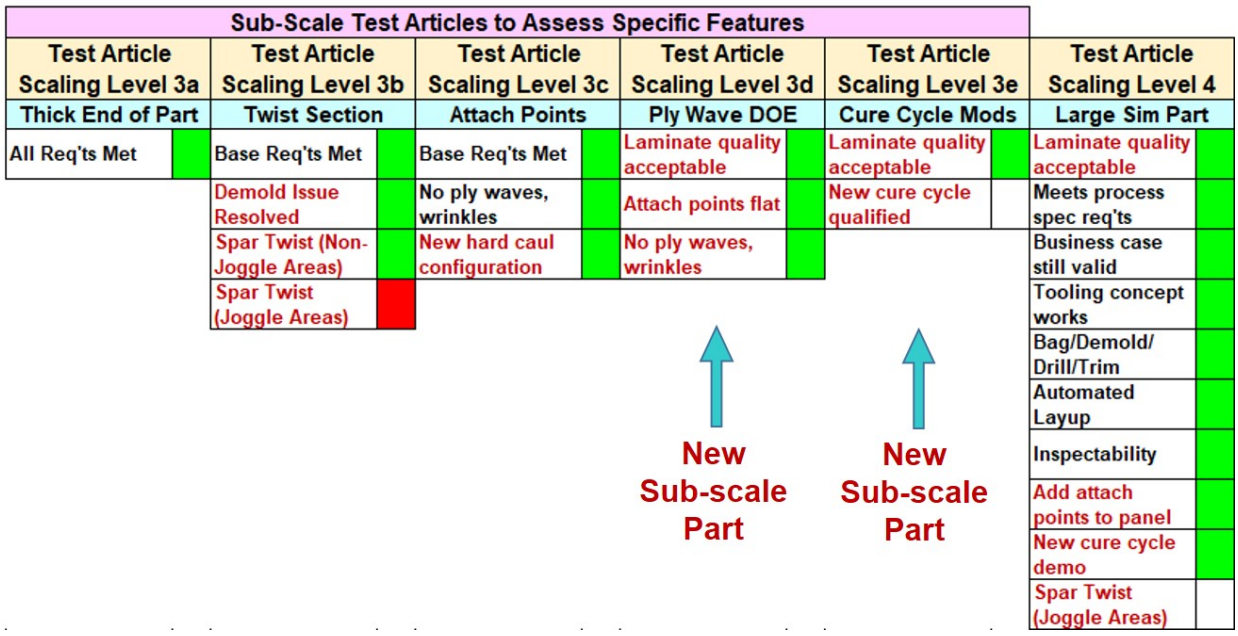


Figure 5. Example Report Illustrating Updated Project Status, and Newly Identified Issues

5. SUMMARY

Measurement of technology maturity via the Technology Readiness Assessment methodology is widely accepted throughout government and industry, and provides a standardized method for technology comparison to support organizational decision-making. The formalized questions used for setting appropriate TRLs are also very helpful in terms of getting project engineers to think through all aspects of their projects.

However, simply reporting technology maturity as a single Technology Readiness Level for an complex developmental project provides management with only a limited understanding of true project status. Reporting by TR Level alone does not provide visibility of the reality that work in complex projects is usually proceeding at multiple scaling levels simultaneously, and does not account for the common situation where technology challenges are confined to small specific part features.

This paper proposes a supplemental reporting vehicle, to be presented to management along with the Technology Readiness Level Assessment. This supplemental report can be easily produced using commercially available spreadsheet software, and shows in table format the "Met/Not Met" status for all requirements at all defined scaling levels for the entire project. This report can evolve as the project progresses, to maintain emphasis on scaling level requirements which remain unmet, especially failed tests where a fix is required.

This new report format communicates a much greater level of technology maturity detail and realism than just the TRL status, while retaining the necessary characteristic that project status can be assessed at a glance.

I wish to gratefully acknowledge the invaluable contributions of Barbara Haynes in organizing and editing this paper and helping me put my ideas together.

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