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Technology readiness assessments: A retrospective

John C. Mankins

Artemis Innovation Management Solutions LLC, Ashburn, VA, USA

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Abstract

The development of new system capabilities typically depends upon the prior success of advanced technology research and development efforts. These systems developments inevitably face the three major challenges of any project: performance, schedule and budget. Done well, advanced technology programs can substantially reduce the uncertainty in all three of these dimensions of project management. Done poorly, or not at all, and new system developments suffer from cost overruns, schedule delays and the steady erosion of initial performance objectives. It is often critical for senior management to be able to determine which of these two paths is more likely—and to respond accordingly. The challenge for system and technology managers is to be able to make clear, well-documented assessments of technology readiness and risks, and to do so at key points in the life cycle of the program.

In the mid 1970s, the National Aeronautics and Space Administration (NASA) introduced the concept of "technology readiness levels" (TRLs) as a discipline-independent, programmatic figure of merit (FOM) to allow more effective assessment of, and communication regarding the maturity of new technologies. In 1995, the TRL scale was further strengthened by the articulation of the first definitions of each level, along with examples (J. Mankins, Technology readiness levels, A White Paper, NASA, Washington, DC, 1995. [1]). Since then, TRLs have been embraced by the U.S. Congress' General Accountability Office (GAO), adopted by the U.S. Department of Defense (DOD), and are being considered for use by numerous other organizations. Overall, the TRLs have proved to be highly effective in communicating the status of new technologies among sometimes diverse organizations.

This paper will review the concept of "technology readiness assessments", and provide a retrospective on the history of "TRLs" during the past 30 years. The paper will conclude with observations concerning prospective future directions for the important discipline of technology readiness assessments.

1. Introduction

The development of new system capabilities typically depends upon the prior success of advanced technology research and development (R&D) efforts. These systems developments inevitably face the three major challenges of any project: performance, schedule and budget. Done well, advanced technology programs can substantially reduce the uncertainty in all three of these dimensions of project management. Done poorly, or not at all, and new system developments suffer from cost overruns, schedule delays and the steady erosion of initial performance objectives. It is often critical for senior management to be able to determine which of these two paths is more likely—and to respond accordingly. The challenge for system and technology managers is to be able to make clear, well-documented assessments

Abbreviations: CSTI, Civil space technology initiative; DOD, (U.S.) department of defense; FOM, Figure of merit; GAO, (U.S.) general accountability office; ITAM, Integrated technology analysis methodology; ITI, Integrated technology index; ITP, Integrated technology plan; JSF, Joint strike fighter; NASA, National aeronautics and space administration; R&D, Research and development; R&D3, R&D degree of difficulty; TFU, Theoretical first unit; TRA, Technology readiness assessment; TRL, Technology readiness level

E-mail address: john.c.mankins@artemisinnovation.com

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2. Technology readiness assessments

TRAs are the points when an organization attempts to determine the maturity of a new technology and/or capability (including required levels of engineering or economics-related performance). In general, a distinct TRA should be conducted at several points during the "life cycle" of a new technology and of new systems. These might include (a) the completion of systems analyzes and conceptual design studies, (b) the point for a decision from among several competing design options, as well as (c) the point of decision to begin full-scale development. Such an assessment might be a small affair, involving just the R&D team, or a large, highly formal process, involving an external, independent peer review process.

To be most effective, the overall R&D organization (and its customers) should seek to conduct more or less formal TRAs, employing the TRLs, and not just individual managers evaluating their own options. Within the US DOD, such formal TRA's have in recent years become policy.

In addition to TRLs, an effective TRA should also incorporate some metric(s) that provide a consistent assessment of the "riskiness" of a new technology development—such as the Research and Development Degree of Difficulty (R&D3) scale. The key data that are necessary to conduct at effective TRA include:

Performance objectives. A clear understanding of the performance objectives for the new technology and/or system capability (including as appropriate both engineering measures of performance, such as mass, as well as operational measures of performance, such as cost, availability, mean-time-between-failure, etc.).

Technology readiness level(s). The current TRL FOR the technology and/or system capability in question, as well as for any key supporting technologies. In a rigorous TRA, this should include some clear evidence that the stated TRL has been achieved—such as a photo of a "breadboard in the laboratory", quantitative data from validation testing, etc.

Research and development degree of difficulty. It is also important during a formal TRA to develop a clear understanding of the remaining "development hurdles" and the projected uncertainty in the likelihood of development success for novel technologies. The R&D3 scale (discussed in more detail in a companion white paper) is one approach to meeting this management need [2].

Quite often, a TRA is conducted in the context of a specific system development effort, perhaps involving several new technology developments. Also, it is also usually important to develop as part of the assessment a clear understanding of the remaining development risks for the new system being developed. In these cases, some additional synthesis of individual TRA results is needed (including TRLs, R&D3, or other measures of uncertainty, and others); in these cases, the Integrated Technology Analysis Methodology (ITAM), including Integrated Technology Index (ITI) for different technologies, may be useful, along with the use of a technology development "risk" matrix, and other tools.

The focus of the paper presented here is on the foundation of modern TRAs: the Technology readiness level scale. The following section provides basic definitions of this broadly used technology management tool.

3. Technology readiness levels: definitions

The following paragraphs provide a descriptive discussion of each technology readiness level, including an example of the type of activities that would characterize each TRL. Fig. 1 provides an overview of the TRL scale, including summary correlations to various stages in technology development and maturation.

3.1. TRL 1: Basic principles observed and reported

"TRL 1" is the lowest "level" of technology maturation. At this level, basic scientific research has resulted in the observation and reporting of basic principles, and these begin to be translated into more applied research and development. Examples of "TRL 1" might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber). Such activities would typically be pursued by scientific research organizations such as the US

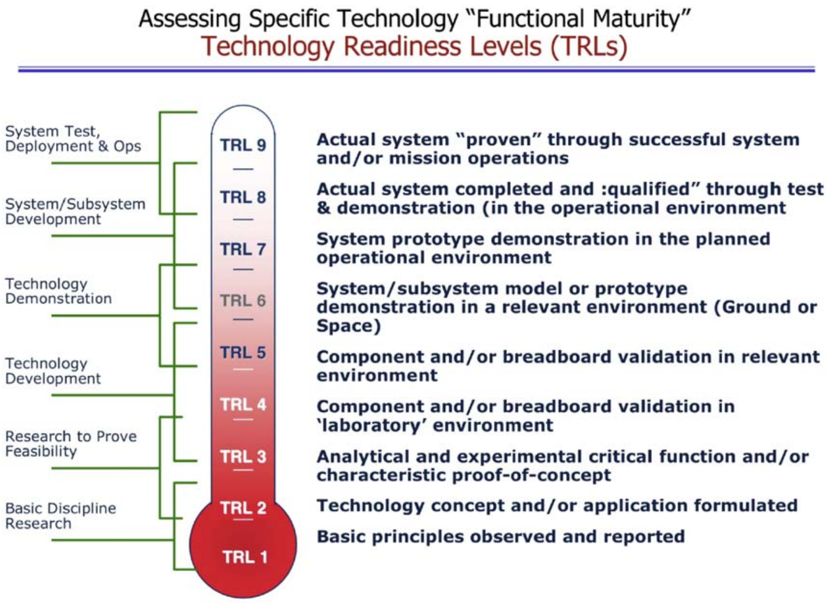

Fig. 1. Overview of the technology readiness level scale.

National Science Foundation, or by individuals such as university researchers.

The costs to achieve "TRL 1" can range from very "low" to very, very high, depending on the discipline are of the research involved. In other words, they may range from a very small fraction of the costs of an eventual system application involving the basic principles being observed, to even more that the system itself. Also, these costs tend to be "unique"—namely, these costs can vary significantly from one research discipline to another. For example, the costs of a fundamental discovery in aerodynamics or biochemistry, using a large infrastructure (wind tunnels or laboratories, and supercomputers) will be significantly greater than that of the discovery of a new computational algorithms, involving one or more researcher, a white board and the desktop computer.

3.2. TRL 2: Technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation—"TRL 2"—practical applications of those characteristics can be identified or "invented". For example, in the late 1980s, following the observation of high critical temperature (Htc) superconductivity in a novel class of materials, potential applications of the new material could then be defined—such as their use in thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors). Similarly, in the 1990s, following the discovery of Buckminster Fullerenes and carbon nanotubes (CNTs), an array of novel applications of this new material were conceived, ranging from improved sensors to "space elevators"! At TRL 2, the applications are still rather speculative; at this point, there is no specific experimental proof or detailed analysis to support the conjecture.

The costs to achieve "TRL 2" are typically "low"—in other words, they usually a very small fraction of the costs of an eventual system application involving the basic principles being observed. Also, as in the case of TRL 1, these costs tend to be "unique"—namely, the costs can vary significantly from one research discipline or invention to the next. Such activities may be undertaken by almost any kind of organization, but would most often arise among universities, small businesses, individual entrepreneurs, etc.

3.3. TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept

At this step in the maturation process, active research and development is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on the use of slush hydrogen or super-cooled hydrogen as a propellant: TRL 3 might be attained when the "right" (i.e., concept-enabling) combination of phase, temperature and pressure for the fluid was achieved in a laboratory.

TRL 3 includes both "analytical" and "experimental" approaches to proving a particular concept. Which approach is appropriate depends in part on the physical phenomena involved in the invention. For example, relatively straightforward physical or chemical systems concepts might be able to be "proven" even at the "chalkboard level". Similarly, new algorithms or computational techniques may be "proven" analytically. However, other inventions will require physical experimental validation—such as those involving highly complicated concepts or those involving environmentally dependent phenomena or novel materials effects.

The costs to achieve "TRL 3" are typically "low to moderate"—in other words, they would usually represent a small to modest fraction of the costs of an eventual system application involving the critical characteristics or functions being proven. Again, these costs tend to be largely "technology unique"—namely, the costs can vary significantly from one area of research and development to another. Such activities might be undertaken by almost any kind of organization, but (because of the increasing costs) would more often involve some formal sponsorship (e.g., through government or industry investments). Because of the relatively high risk and long lead times, it is less likely that funding at TRL 3 or below would be available from most types of venture funding sources.

3.4. TRL 4: Component and/or breadboard validation in a laboratory environment

Following successful "proof-of-concept" for critical functions or characteristics, the basic technological elements involved in an invention must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance at the level of a component and/or breadboard. This validation at "TRL 4" must be devised to best support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. However, validation at this level is relatively "low-fidelity" compared to the eventual system applications.

Validation at TRL 4 could involve the "patchcord" integration and testing of ad hoc discrete electronic components in a laboratory. Alternatively, a TRL 4 demonstration of a new "fuzzy logic" approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.

In the case of "TRL 4", costs might typically be expected to be "moderate". In other words, they would usually be a modest fraction of the costs of an eventual system application involving the concepts and components being tested. Again, these costs tend to be largely "technology specific"—but, would most likely be greater (perhaps several times greater) than the investment(s) required to achieve TRL 3 in the same topic. Such activities could be undertaken by various formal R&D organizations, but (because of the increasing costs) would very likely involve some formal sponsorship (e.g., through government or industry investments). Because of the decreasing risk and reduced lead times, it is more likely that funding at TRL 4 or greater could (in appropriate cases) come from most types of venture funding sources.

3.5. TRL 5: Component and/or breadboard validation in relevant environment

At TRL 5, the fidelity of the component and/or breadboard being tested increases significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a "simulated" or somewhat realistic environment. From one-to-several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array "blanket" that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.

In this case, R&D costs might typically be expected to still be "moderate to high", and would tend to be largely "technology specific". These costs would most likely be similar to, but greater than (perhaps two or more times greater) than the investment(s) required to achieve TRL 4 in the same topic area. These activities would almost certainly be undertaken by a formal R&D organization (such as a corporate laboratory), but (because of the increasing costs) would very likely involve some formal sponsorship (e.g., through government or industry investments, or venture funding where appropriate).

3.6. TRL 6: System/sub-system model or prototype demonstration in a relevant environment

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system—which would go well beyond ad hoc, "patch-cord" or discrete component level "bread boarding"—would be tested in a relevant environment. At this level, if the only "relevant environment" is the environment of space, the model and/or prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies.

At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station (ISS) "pallet". In this example, the reason space is the "relevant" environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system—and the only way to validate the technology is in space.

For TRL 6, R&D costs might typically be expected to be "high", and would tend to be largely "specific to the technology or demonstration to be performed". These costs would most likely be similar to, but less than (perhaps a factor of two or more times less) the investment(s) to reach TRL 7 (see below) in the same topic area. These activities could only be undertaken by an appropriate formal "project-like" organization, and (because of the significantly increased costs) would almost always involve formal sponsorship (e.g., through government or industry investments, or venture funding where appropriate).

3.7. TRL 7: System prototype demonstration in the expected operational environment

TRL 7 is a significant maturation step beyond TRL 6, requiring an actual system prototype demonstration in the expected operational environment (e.g., in space in the case of NASA). It has not always been implemented in past programs and is not always necessary. In the case of TRL 7, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in the actual expected operational environment. The driving purpose for achieving this level of maturity must be tied to assuring system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of an actual planned application. Of course, not all technologies in all systems must be demonstrated at this level.

This programmatic maturation step would normally only be performed in cases where the technology and/or sub-system application is both mission critical and relatively high risk. Example: the Mars Pathfinder Rover was a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Some examples include: "X-vehicles" (such as the demonstration aircraft in the Joint Strike Fighter (JSF) program) are TRL 7, as are major technology demonstration projects (such as those planned during the 1990s as part of NASA's New millennium spacecraft program).

For TRL 7, R&D costs would typically be "very high", and could be a significant fraction of the cost to develop the ultimate system application, depending on the scale and the fidelity of the system prototype demonstration being implemented. (In the original NASA nomenclature, these costs could be a significant fraction of the costs of "Phase C/D to theoretical first unit (TFU)"— i.e., the costs of "system design and development through the TFU".) These costs would most likely be similar to, but greater than (perhaps two or more times greater) the investment(s) to reach TRL 6 (see above) in the same topic area. These activities could only be undertaken by an appropriate formal "project" organization, and (because of the dramatically increased costs) would always involve formal sponsorship (e.g., through government or industry investments, or venture funding where appropriate).

3.8. TRL 8: Actual system completed and "qualified" through test and demonstration

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true "system development" for most technology elements. Example: in the case of a space system being development by NASA, TRL 8 might include the Design, Development, Test and Evaluation (DDT&E) through theoretical first unit for a new type of personnel launch vehicle. TRL 8 might also involve cases in which a new technology is being integrated into an existing system (rather than the development of an entirely new system). Example: developing, loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while it is in orbit could comprise TRL 8.

These costs are specific to the mission and functional requirements that the new system must address, but would be typically "very high". In fact, these costs would, in most cases, be greater than the combined costs of all prior TRL levels by a factor of 5–10 times. (In the original NASA nomenclature, these costs could be a significant fraction of the costs of "Phase C/D to TFU"—i.e., the costs of "system design and development through the theoretical first unit".) These costs would most likely be similar to, but greater than (perhaps two or more times greater) the investment(s) to reach TRL 6 (see above) in the same topic area. Of course, system development efforts would in almost all cases only be undertaken by an appropriate and highly formal "project" organization, and (because of the dramatically increased costs) would always involve formal sponsorship (e.g., through government or industry investments, or venture funding where appropriate).

3.9. TRL 9: Actual system "flight proven" through successful mission operations

By definition, all technologies that succeed in being applied in actual systems go eventually to TRL 9. However, in almost all cases, the end of last "bug fixing" aspects of true "system development" do not occur until an actual system is first deployed; this is "TRL 9". For example, in a space system, there may be a need for small fixes (such as a software change) or changes operational procedures to address problems found following launch (typically, through a period of some "30 days" following launch). Such changes might include integration of new technology into an existing system (such operating a new artificial intelligence tool into an operational mission control center, such as the one at the NASA Johnson Space Center (JSC)).

The central difference between TRLs 8 and 9 is "operations". So, building a new aircraft, or spacecraft is TRL 8. Launching that spacecraft or aircraft and operating it during an actual mission is TRL 9. However, this TRL does not typically include pre-planned product improvement (P3I) of ongoing or reusable systems. For example, a new engine for an existing reusable launch vehicle (RLV) would not start at TRL 9: such "technology" upgrades would start over at the appropriate level in the TRL system.

These costs are specific to the mission to be accomplished; they would be typically "high", but usually significantly less than the cost of TRL 8 (full-scale system development). Obviously, these activities could only be undertaken by a formal "mission" or "operations" organization.

4. The emergence of TRLs

The TRL scale did not emerge all at once. Rather, it emerged in several stages—and, similarly won acceptance within the aerospace and advanced technology systems management community only over a period of several decades. The following section provides an overview of this process of emergence. Fig. 2 summarizes the process.

4.1. 1960s–1970s

The idea of articulating the status of a new technology planned for use in a future space system was clearly stated as early as 1969. In this context, the correlation was between the then-established practice of the "flight readiness review", and a new idea through which the level of maturity of new technologies could be assessed: the "technology readiness review". This idea is found in a 1969 report on advanced space station technology requirements.

In the mid 1970s, the idea of developing an actual technology-independent scale for assessments was invented. The National Aeronautics and Space Administration, Office of Aeronautics and Space Technology (OAST) originally developed in the late 1970s the concept of "technology readiness levels" as a systematic tool that enables assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.

The original TRL scale was devised within NASA by Mr. Stan Sadin of the Office of Aeronautics and Space Technology, as part of the effort to develop a "systems-technology model" for the Agency.

The early versions of the TRL scale consisted of either six or seven levels, with brief one-line characterizations of the definition of each level.

4.2. 1980s–1990s

In the mid-to-later 1980s, NASA suffered the loss of the Challenger Space Shuttle. This terrible accident resulted, however, in an increased emphasis on rebuilding the space agency's technological foundations through new, "focused" programs: the Civil Space Technology Initiatives (CSTI) and "Project Pathfinder". Due to their emphasis on moving advanced technologies through

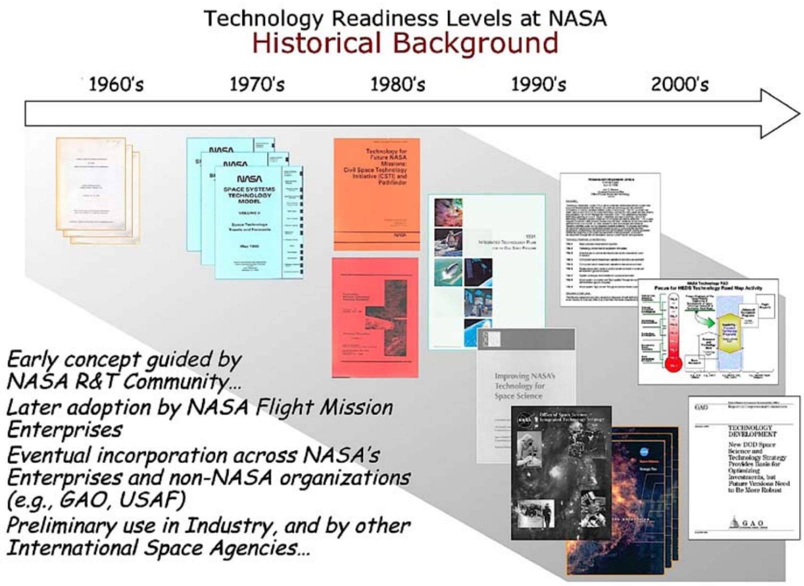

Fig. 2. Timeline for the emergence of the TRL scale.

research to maturation to applications in a better-managed approach, the use of the TRL scale to assess and communicate that status of a wide range of new technologies became more widely accepted. This use of TRLs continued and expanded following the announcement of the new "Space Exploration Initiative" (SEI) in July 1989 due to the need to communicate technology readiness status and forecasts between the technology research community and the exploration mission planning community. At this time, the TRL scale was extended from six/seven levels to the nine levels that are now the standard.[1]

Then, in 1991 NASA developed (in response to the recommendations of the advisory panel on the future of the Civil Space Program; the so-called "Augustine Report"), the first strategically-oriented "Integrated Technology Plan for the Civil Space Program" (the "ITP") [3]. The planning process that resulted in this document involved 1000's of work hours and 100s of individuals—and it employed the then newly expanded TRL scale to coordinate the entirety of the technology assessments and forecasts that formed the foundation for the integrated plan. Mirror documents—integrated technology strategies—were developed by NASA's office of space science in the early-to-mid 1990s, and these once again exploited the TRL scale extensively. Here, for the first time, a science organization used the scale both for management it's own instrument technology programs, and also for communicating more effectively with technology researchers and organizations inside and outside NASA.

Then, in the mid 1990s, the author was responsible for drafting the first comprehensive set of definitions of the technology readiness levels (a white paper, 1995). This set formed the basis in 1999 for the recommendation by the U.S. General Accountability Office to the Department of Defense that they should adopt the NASA scale—or invent a similar management tool of their own—in order to improve the quality of DOD technology R&D outcomes [4], In 2000, DOD formally adopted NASA's TRL scales [5].

4.3. Early 2000s

Given the adoption of TRLs by DOD, the TRL scale achieved wide-spread adoption—both by the various agencies within the DOD, and by their far-flung contractor teams. By the early 2000s, the scale was being examined for use by international space agencies and their contractors; and, versions of the TRL scale were in use in Japan, France, and elsewhere in Europe through the European Space Agency. By the 2005–2006 timeframe, the standard version of the TRL scale had been formally adopted world-wide.

5. Challenges and directions

There are a range of challenges, both organizational and methodological facing the technology assessment

[1] TRL levels 8 and 9 were added by the author.

community. For example, achieving the right level of technology maturity across multiple subsystems and components is an ongoing challenge to development success of all advanced technology systems. Establishing the right metrics for these technology/systems developments is essential; these must include a variety of performance and cost figures of merit. However, assuring consistent assessment of technology metrics, readiness, progress is also critical, including early and ongoing modeling of new systems and technologies (that is accessible to various parties in the R&T / systems development process).

Another challenge is the need for technology management FOMs that concern the riskiness of a new technology development. There is a real need for practices and metrics that allow assessment of anticipated research and development uncertainty. One such example is the "research and development degree of difficulty".

6. Summary

This paper has provided a retrospective on the history of "TRLs" during the past thirty years. The paper also offered selected observations concerning prospective future directions for the important discipline of technology readiness assessments.

The TRL scale has made a substantial contribution to the discipline of technology readiness assessment. And, the scale is likely to continue to play an increasingly significant role in the future of technology and systems management as systems become more and more dependent on concurrent developments in multiple technology areas, and as the use of TRLs becomes more and more wide spread.

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