USE OF TECHNOLOGY READINESS LEVELS AS A DEVELOPMENT TOOL

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Introduction

Technology Readiness Levels (TRLs) are a means to categorize the relative technical maturity of components, sub-systems, or systems. Technological or technical maturity is a measure of performance, reliability, durability, and operating experience, and more technologically mature components (better performing, more reliable, more durable, greater operating experience) are rated higher than experimental or prototype components or systems. In this definition, an understanding of the supporting terms is important, and these also have specific meanings. Performance is the component's or system's ability to perform the task for which is intended. Reliability is a measure of repeatability or consistency, or the ability of a component or system to perform at a particular level for sustained periods of operation. Durability is the ability of the component or system to withstand stresses and wear without a degradation or failure in performance. Increased operating experience is correlated with higher technical maturity because it provides more data to support more accurate assessments of performance, reliability, and durability, which in turn support optimization of design and functionality.

Various government agencies and research programs are now using TRLs to assess the technological maturity of components and systems in order to drive the technology development process. The National Aeronautics and Space Administration (NASA), the U.S. Department of Defense (DoD), and the DOE Office of Environmental Management (DOE-EM) employ an integer rating system that spans from 1 to 9, with the lowest number corresponding to "basic principles observed" and the highest number corresponding to "mission proven." The Next Generation Nuclear Plant (NGNP) Project, which is funded by the DOE Office of Nuclear Energy (DOE-NE), is adopting the NASA and DoD systems to govern its work, while the DOE Nuclear Hydrogen Initiative (also DOE-NE) and the DOE Hydrogen Program (DOE Office of Energy Efficiency and Renewable Energy, EERE) are exploring systems that span 1 to 6 and 1 to 8, respectively.

By themselves, TRLs are abstractions that help facilitate the communication of complex ideas between developers and project stakeholders; that is, between scientists and engineers, who tend to be highly technical, and program managers and sponsors, who tend to be less technical. For example, instead of a developer discussing with a program sponsor whether the latest design of Device X is operating at 23% efficiency with a mean time between failures of 650 hours, a developer can instead reference a TRL in the discussion. Since a common understanding of what that TRL means in terms of performance, reliability, durability, and operating experience will have been previously established, less confusion would result. If there is only one component or system under development by the program, then the facilitation is moot, but it becomes much easier to use TRLs in such discussions rather than direct technical data when the number of components or systems under development is greater than just a few, and each component or system under development is designed for a different purpose.

Additional value is drawn from TRLs by virtue of the programmatic infrastructure needed to support the TRL assessment system. Assigning a TRL requires the establishment of an objective entry and assessment process, identification of expected component or system performance at each stage of development, and application of quality assurance processes for technical data and other supporting records. As a natural extension, such processes also almost automatically lead to the identification and generation of information that can be used to support intellectual property claims.

The use of TRLs is a risk reduction strategy. A component's or system's TRL is loosely correlated with the capital and operating cost required to perform a test in order to verify that a particular component or system is at a particular TLR. For example, it is usually cheaper to perform a test of a small prototype component in the laboratory in order to provide proof-of-principle than it is to perform long duration testing of a full-sized component in an operational or plant environment. TRLs are also indicative of risk, and lower TRLs, due to lack of data or inherent design problems, are correlated with a higher probability of failure. In a development process, only successful tests lead to higher technical maturity, while failed tests either lead to lost investment or higher investment if tests must be repeated. Therefore, greater programmatic efficiencies (lower overall costs) may be realized if the capital and operating investments made into testing a component or system are scaled appropriately to the current testing phase and target TRLs.

Successful use of TRLs by a development program requires the sustained support of program management, and active management of the supporting processes.

In this paper, existing TRL systems are discussed. The mechanics of managing and using a TRL system are described. Further details about how components, sub-systems, or systems may be initially assessed (the entry process) and promoted are provided. The importance of building development case files and maintaining records is highlighted. Also, a more thorough discussion of communications and risk is undertaken in order to highlight the advantages of using TRLs as a tool to help manage large technology development projects.

TRL Scales

The model system is one established by NASA in the 1990's, and is used to categorize the relative technological maturity of components, sub-systems, and systems [1, 2]. Definitions of the NASA TRLs are given in Table 1.

After NASA adopted its system, other parts of the U.S. government adapted the NASA TRL definitions to their own needs, and now DoD [3] and DOE-EM [4] use similar scales to the NASA scale. In these other systems, the number of TRLs are the same, and the higher-level definitions are the same (shown in bold in Table 1), but the individual interpretation of the higher-level definitions (shown in regular text in Table 1) are altered to meet the needs of the individual research and development programs.

Other government-sponsored research and development programs are following in the path prepared by NASA, DoD, and DOE-EM and are working to develop their own TRL systems, but are changing the number of levels employed to assess technological readiness. The DOE Nuclear Hydrogen Initiative (NHI) out of the DOE Office of Nuclear Energy (DOE-NE) has offered a system that has six levels [5]. The DOE Office of Energy Efficiency and Renewable Energy (DOE-EERE) Hydrogen Program is working on a system with 8 levels. The Next Generation Nuclear Plant (NGNP) Project, also out of the DOE-NE, is developing a system with 10 levels. These other scales are not a departure from the original NASA model, but instead combine or expand elements of the NASA scale to provide more or less emphasis on different stages of development. Mapping the definitions of the TRLs in these scales to each

Table 1: **NASA TRL System**

Level	Description
1	**Basic Principles Observed and Reported.** Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies on 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 analyses to support assumptions. Examples are limited to analytical 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 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 to 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 it 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 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, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
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 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.

other (see Figure 1) shows that the scales are all roughly equivalent and use similar definitions.

Development Phases and Decision Gates

Defining the meaning of the various TRLs is only part of the story, and the real usefulness of employing a TRL system is how it can be used to control the research and development (R&D) process

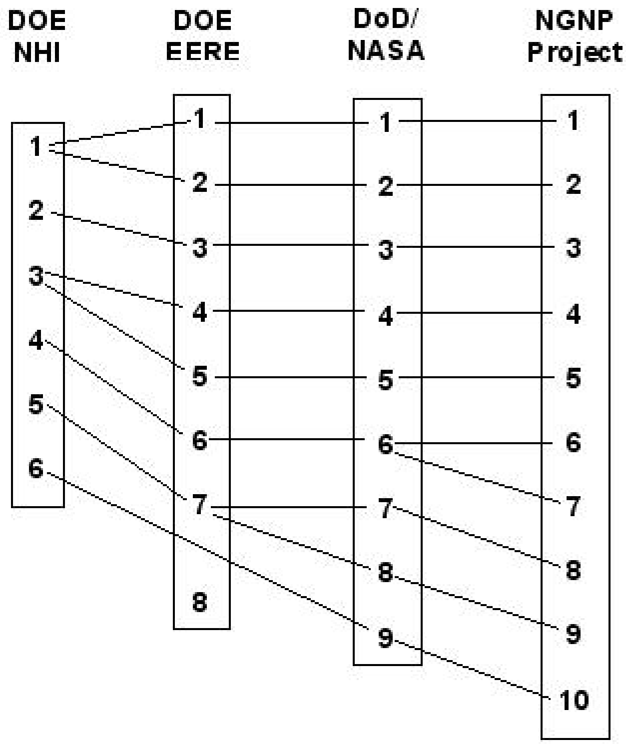

Figure 1: Equivalence mapping of various TRL scales.

and drive development activities. A TRL system is organized as a series of development phases and decision gates, as shown in Figure 2.

Figure 2: Phase-gate progression for TRL systems.

A development phase is an activity that corresponds to the development work that is needed to achieve a particular TRL, and a decision gate is the point at which a component, sub-system, or system is evaluated and compared to the criteria that must be met in order to achieve the gate's particular TRL. A technology must pass successfully through a gate in order to achieve the gate's TRL. For example, a technology rated at TRL N-1 is undergoing Phase N development. Upon completing the Phase N development activities, the technology is evaluated at Gate N and it is determined that all Gate N success criteria have been met. At that point, the TRL of the technology is increased to N, and the technology becomes eligible for Phase N+1 development. Achievement of the success criteria at a decision gate is a necessary but not sufficient condition to enter into the next phase of development. Sufficient funding and resources are also needed to perform the development work, and advancement of the technology must be supported by the project or program management, and the sponsor for the work.

Technology developers perform the development phases, while assigned evaluators (who ideally are independent from the developers) control the decision gates. Gate decisions are also influenced by the governing program or project manager. An evaluator, based on the information provided by the technology developer, may recommend advancement, or may choose different paths. If the information provided by the technology developer is incomplete, the evaluator may recommend further work in the current R&D phase in order to fill in the gaps. The evaluator may also reject the technology altogether if it appears that the success criteria were not met and may never be met, regardless of how much more effort or funding is expended to achieve the success criteria for the gate. These decision options are illustrated in Figure 3.

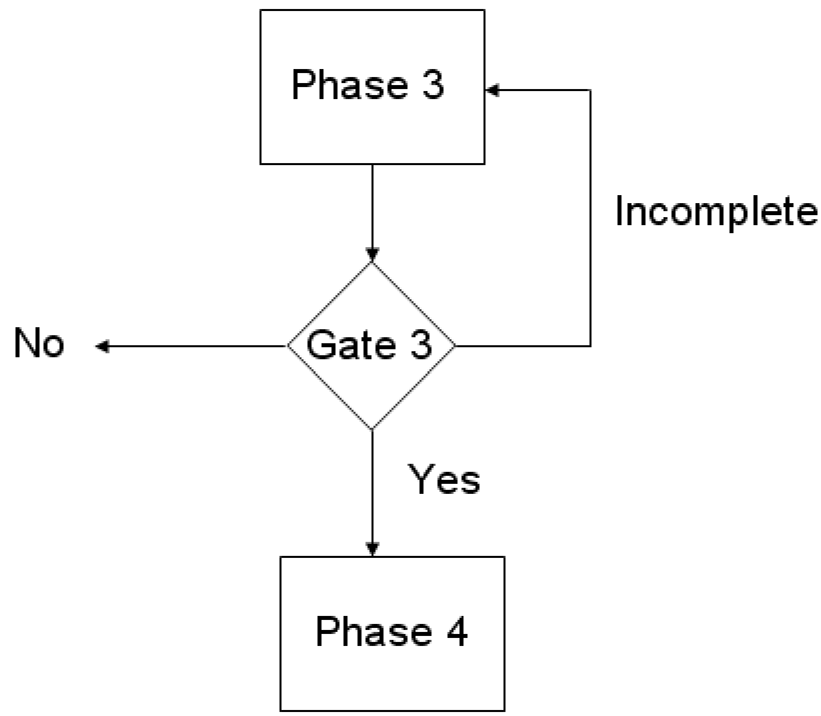

Figure 3: Decision gate options.

Gate decisions are made on a pass-fail basis, and each component, sub-system, or system is evaluated independently of other candidate technologies for a given application. Information collected during the decision gate evaluation process can be used, however, to determine the relative merits of competing technologies, and to determine which of the competing technologies has better performance, lower cost, or greater reliability or robustness. Such decisions are project/program management decisions and fall outside of the scope of the TRL systems described here.

Using a phase-gate process to perform technology development encourages the use of quality assurance tools and the maintenance of development records. Performing a decision gate evaluation will require that information on a particular technology be compiled and assembled in a coherent form and that the information submitted is correct or at least accurate. This in turn will require some level of peer review of the data, which pushes for standardized quality assurance measures for how the work is performed and how the data on a particular technology is recorded and stored. Such information is conveniently stored in a component's or system's case file, which holds all of the records pertaining to a component's or system's development. As a by-product of this process, information to support future intellectual property claims is created almost automatically and can be obtained from the data stored in the case files.

Entry Process

All of the TRL systems described require an entry process. The entry process is a screening process that is used to determine whether an idea, concept, design, or candidate technology may be capable of performing a given task, and that an achievable development path can be envisioned. If development is warrented, a case file is created for the particular technology, and initial screening information is placed into the case file. The entry process is essentially a decision gate, and the process used to perform the evaluation is the same as for the other gates. Unlike the TRL decision gates, the entry gate sits outside of the normal linear progression of the TRL phases and gates and can feed a candidate technology into any of the development phases, as appropriate to the initially assessed level of technology readiness for a given application.

Risk Reduction

Implied in the TRL systems are the assumptions that greater TRLs correspond to greater reliability, that technologies with higher TRLs function more closely to the desired end-state of the technology, and that the cost of performing a validation test increases as the fidelity of testing begins to approach actual end-use conditions. Reliability is the probability of achieving the same result upon repeated trials. The converse of reliability is the probability of failure, or the probability of not achieving the same result upon repeated trials. Advancement through a decision gate requires the performance of one or more successful tests or experiments where success is defined as an outcome meeting or exceeding selected success criteria, and a failed experiment or test represents a "loss" in economic terms in the development process. A failed experiment or test either results in the need to repeat an experiment or test after additional development work (greater cost), or rejection of the technology (loss of investment). Given the directional preference of decision gates ("only successful experiments or tests lead to advancement"), it is better from an investment standpoint to perform less expensive experiments or tests at lower development phases because the cumulative penalty (number of failed experiments times the cost per experiment) may be reduced. At higher TRLs, reliability is greater, so more realistic (and presumably more expensive) tests can be performed with less risk of incurring greater costs or losing the investment. The relationships between investment costs, probabilities of failure, and TRLs are shown qualitatively in Figure 4.

In some cases, costs savings may be achieved by skipping one or more development phases. This may be preferred when the cost of a higher fidelity test is lower than the cost of a lower fidelity test, and the impact of a failure on other related components or systems is minimal. For example, if a large-scale pilot plant with the capacity to test components exists and is currently in operation, then it may be more practical to perform a component test in the actual pilot plant than it would be to build a dedicated test rig and perform experiments on the component in the laboratory prior to testing the component in the pilot plant.

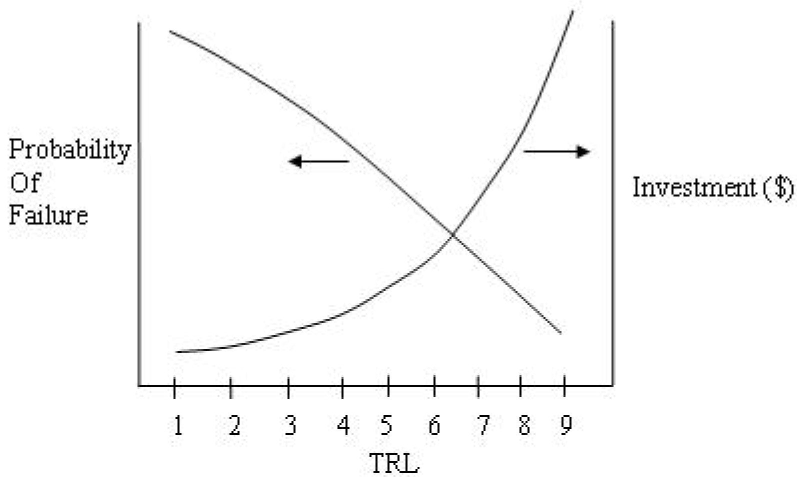

Figure 4: Relationships between investment cost, TRL, and probability of failure.

Management and Communication Tool

Using a TRL system to manage larger technology development projects, regardless of the number of TRLs used or the exact definition of what each TRL means to the development program, can be an organizing framework around which R&D is conducted. Researchers, developers, project/program managers, and program sponsors agree upon a given TRL system, and assume its methods and definitions as a common way of doing business. The TRLs and the development phases then can become a shorthand language that enables people of different technical backgrounds to communicate without getting lost in the details of any particular technology. For the researchers, the requirements for achieving a particular technology readiness level can be translated into technical performance criteria and supporting experiments, while managers and sponsors can interpret the same TRL in the context of project risk, costs, and impact of development activities on a development program's schedule and budget. The progressive nature of the TRL systems establishes a development direction (lower to higher technological maturity) that can be understood by all, and allows for the comparison of competing technologies on a common basis.

Adopting a TRL system separates the development process from the development activities, and this allows for more management control and better definition of what activities and information are needed to achieve higher technology readiness. It divides development work into distinct phases that can be handled in discrete units, which aids in management of the development program. Without explicitly established technology targets, research and development programs may be subject to scope drift, perpetual development, and lack of a clear message to program sponsors. Use of a TRL system to manage development helps prevent these problems, and will help to provide assurance to sponsors and stakeholders that development activities are purposeful and are directed towards achieving specific goals.

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