Detailed Definitions and Guidance for Application of Technology Readiness Levels

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Introduction

IT has been common to judge the relative "goodness" of something by using a numerical scale to assess gradations of that goodness. The technology readiness level (TRL) scale does seem to be universally accepted, but there is a need for detailed definitions of each level to aid in the planning process. The detailed definitions given in this Note were developed as part of the National Fixed Wing Vehicle program. The focus was on the TRLs applicable to Science and Technology (S&T), i.e., the portion where the greatest variability from interpretation is likely to be. It is suggested that the extreme values of the scale are not as ambiguous, although this is discussed later. A primary factor in this approach is the judgment of how risk for system application reduces as technology maturity increases. This is illustrated in Fig. 1, with consideration of risk for technology application in the phases of system acquisition. S&T is typically considered to develop technology for input to the demonstration/validation phase with TRL 6 (acceptable risk) or 5 (high risk). These definitions are intended to help program management decisions.

Technology Readiness Levels

Before discussing the individual levels, we define some of the terminology that will be used:

1) *Hardware* is any piece of physical equipment that is part of the technology under consideration. This should be construed in a general sense so that it could be a structural component, or a wind-tunnel model, etc.

2) *Model* is the next term, which is the analytical model, i.e., the complete description of the performance and cost of the technology. This term can include empirical models based on wind-tunnel data, physics-based models, or simulation models that are a composite. The engineer applying the TRL approach has to make a judgment about the fidelity of the model.

3) The *test environment* is the set of parameters of the demonstration or test that provide the data to define the TRL. For example, the parameters of a wind-tunnel test would include scale, Reynolds and Mach numbers, etc., to assess the reliability vs the full-scale aircraft conditions. Component tests would be judged based on scale, environmental conditions, etc. There will be a progression to integrated testing, where interactions will represent the actual operation more closely.

4) *Products* are the data that are available from the activity defining the TRL. This will range from analytical calculations through ground testing and flight demonstration results. The product can be interpreted as deliverable from a technology program.

5) *Uncertainty* is an assessment of the demonstration data products that relate any uncertainties in the technology model to the risk of system integration.

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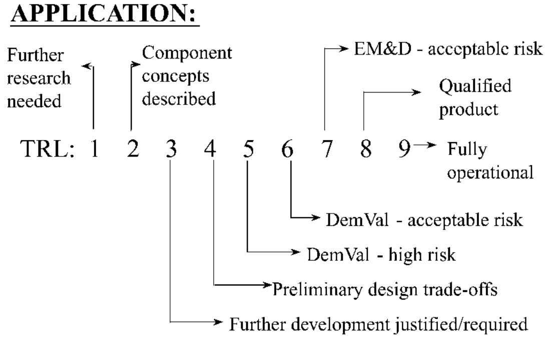

Fig. 1 Progression of system application risk vs TRL.

6) *Risk* is the judgment of probability and consequence to the system application of failure of that technology to match predictions adequately.

7) *Transition readiness* is the judgment of how ready the technology is for incorporation into the development phase of a system application.

Now we can discuss the details of each of the levels that were considered.

Technology Readiness Levels 1 and 2

These levels were not addressed in much detail in the aforementioned process, but would need to be included if we are considering elements of basic research, i.e., basic principles or a technology concept. The typical case will be analytical or theoretical predictions with no supporting test data. It would also be appropriate to assign these levels for cases of incomplete experimental data, e.g., TRL 1 for an experiment with incomplete documentation of control parameters, or TRL 2 for an experiment that was done with no theoretical analysis. In either case models could be considered order-of-magnitude approximations for performance. For system application feasibility is unknown so that there is major risk because of the uncertainties.

Technology Readiness Level 3

This level applies when analytical and experimental evidence is available to identify critical functions and/or characteristics so that the concept is considered to be proven. Testing of breadboard or generic hardware should have been accomplished. Examples could be parametric wind-tunnel testing or partial testing of subscale components. First-order analytical models should have been developed. The contributions of the technology toward the goals of the planned application should have been predicted, but not correlated with data directly for the planned configuration. Examples could be detailed computational fluid dynamics predictions, or using extrapolations from test data. In addition, predictions of benefits would typically be for a single technology so that system integration and interactions are unknown. The products would be technology models but with many uncertainties. At this TRL the technology characteristics are being defined. The concept has been justified as worth further development, and there is potential transition for system applications. The uncertainties are with system integration, and so there is still major risk.

Technology Readiness Level 4

This level applies when there has been component and/or breadboard validation of hardware that is representative of the technical concept showing that the approach is suitable for flight articles. A laboratory, in the general sense, is considered to be the relevant test environment. This could include a wind-tunnel test of the chosen configuration at the appropriate Reynolds and Mach numbers or a simulation of moderate fidelity. Analytical models will have been defined and correlations made with initial test data. Cost predictions will have been made, but that will be discussed later in the paper. The products for this level are models that are credible for design and performance predictions. At this level the technology is definitely appropriate for use in design tradeoffs. Actual test data show that the technology can probably be transitioned to system application, but the integration issues are still not well defined.

Technology Readiness Level 5

This level applies when there has been component and/or breadboard validation in a relevant environment. In contrast with TRL 4, the testing must be of hardware of appropriate scale and functionally equivalent to flight articles. The hardware may not be flight weight, representative material, etc., but judgment should be used to assess risk depending on the criticality of those properties to the application. Also, at this level the relevant test environment is a high-fidelity ground demonstration or a simulation with system interactions identified. There should be analytical models of the technology integrated into the system, including test correlations made with good agreement. The products will be models with good estimates of performance (and cost impacts). The technology is ready for detailed design studies, and uncertainties can be judged to be medium. The integration issues have been defined, and the technology potential for transition can be considered good, but still high risk for Engineering Management and Development (EMD).

Technology Readiness Level 6

This level applies when there has been system/subsystem, model, or prototype demonstration in a relevant environment. The tested hardware must be of full scale, and the hardware must be actual flight articles or flight type to be above TRL 5. At this level the relevant test environment is either a high-fidelity ground demonstration or simulation with components that could fly, or a low-fidelity flight test, e.g., flight in a restricted flight envelope. There is now an analytical model of the technology as integrated into the flight system, well correlated with test data and showing acceptable uncertainties. The products are substantiated performance and design data, with cost predictions supported by some actual data. Actual test data showing minor risk for transition and integration of the technology into the flight system are well defined. At this level technology has an acceptable risk for incorporation in a demonstration/validation phase, but input into the EMD phase would be judged medium to high risk.

Technology Readiness Level 7

This level applies when there has been system prototype demonstration in an operational environment. At this level the hardware being tested must be full-scale actual flight articles. The relevant environment is flight in the appropriate envelope, i.e., the planned system operational envelope for safety-critical technologies. Alternatively, a ground demonstration of flight hardware might be considered appropriate for noncritical technologies provided the test replicated governing flight conditions such as loads, temperatures, etc. Analytical and simulation models will have high-fidelity, fully validated with test data at operational conditions. Uncertainty is low, and system integration has been demonstrated. The products will be design criteria with validated performance, validated to the point that it could be used with some confidence on a different application (but downgraded to maybe TRL 6). Cost predictions will be supported by data from manufacture and operation of the test articles. The technology is well substantiated with realistic test data and validated as being ready for low-risk transition to EMD.

Project Application of TRLs

TRLs have been used on some projects, but they are not yet widespread. Reference 1 represents recommendations that their use be standard for development of technology. That reference also presents examples of the use in a variety of different applications, although some of the examples are "after-the-fact" analyses. In considering the use of new technology for a potential system acquisition, the risk that can be expected is the major factor as alluded to in Fig. 1. It is possible to provide an analogous detailed progression of risk from the preceding TRL definitions. For illustration, consider an unmanned air vehicle (UAV) application with a judgment of near-term and midterm (5–10 year) developments. Table 1 provides detailed guidance on how the risk would be assessed to augment the application of the detailed definitions of TRL in laying out a required technology program for the project. Then, it is straightforward to use the TRL definitions for exit criteria on a roadmap. A phase or task that included a restricted wind-tunnel test, e.g., parametric technology variations or only low speed, etc., would support raising the TRL to 3. In principle, those results could feed into the next task on the roadmap. That next task could be a high-fidelity wind-tunnel test (TRL 4) or testing of functionally equivalent flight articles (TRL 5). The process would put rigorous criteria into what had to be accomplished by the various tasks on the roadmap and ensure consistency.

Table 1 Detailed definitions of risk progression

TRL	Risk	Risk definition
9	Zero (0)	Successfully demonstrated in UAV ops.
8	Low (1)	Concept demonstrated in UAVs Successfully demonstrated, not in UAVs
7	Acceptable (2)	Problems identified and solutions known based on UAV development Concept demonstrated, but not in UAVs
6	Medium (3)	Current advanced development can probably be accomplished within cost/time schedule; problems of application to UAVs are identified; negligible possibility of failure
5	Medium (4)	Advanced development can incur cost/time overruns, but very low possibility of failure for near term (1 year)
4	Medium (5)	Possibility of failure to meet near-term needs; negligible possibility of failure for midterm (5–10 years)
3	High (6)	Long-term development with estimated costs; very low possibility of failure for midterm application
2	High (7)	Costs largely unknown; low possibility of failure for midterm; parallel efforts desirable
1	V. high (8)	Concepts indicating high potential payoff, but technology may not be feasible now; possibility of failure through midterm; parallel efforts mandatory

Cost Aspects

There is a cost implication in all of the definitions just given, but any discussion is speculative because it is not possible frequently to separate out the cost of an individual technology. There are examples of system cost overrun in Ref. 1, but it is pointed out that technology immaturity is only one factor. We can assume that cost predictions are not made until TRL 3 and that costs are known at TRL 9. In a form that is consistent with the preceding technical definitions, we can define tasks to predict the incremental effects of the technology on cost that are applicable for each level:

1) TRL 3: Initial estimates have been made to assess the direct cost of developing and maturing the individual technology. For example, the cost of required wind-tunnel tests or structural coupon tests can be estimated with reasonable confidence. Return on investment has been calculated.

2) TRL 4: Estimates have been made to assess the cost impacts of the technology integrated into a system. These estimates can be based on statistical data.

3) TRL 5: Initial cost estimates have been made for development, production, and ownership. Departures from database validity have been identified, so that there may be some prediction of variability about the likely cost.

4) TRL 6: Some actual hardware will have been built for this TRL so that some data are available. Also, relative to the planned system application, there will have been planning of all tasks and activities in EMD, production, operation, and support.

5) TRL 7: Actual fabrication of major components has to be accomplished to support this TRL. Also, detailed planning will have been accomplished.

Even the preceding definition of the tasks is very subjective and only provides the most general guidance. First, we need to consider

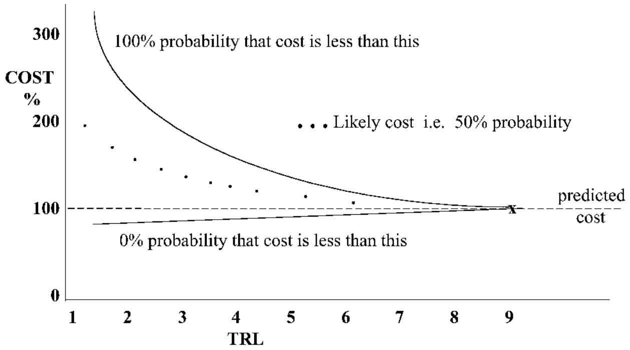

Fig. 2 Heuristic variation of technology cost with TRL.

the prediction of costs without "management reserve" or a factor to cover "unknown unknowns." Following the preceding technical definitions for each TRL, then there is obviously more uncertainty on this predicted cost at the lower TRLs. We know absolutely, however, that there is a 100% probability that costs will be less than an upper bound and also 0% probability that costs will be less than a lower bound (neither of which will be known, in practice). Only if the uncertainties are random can we assume that the most likely cost is the 50% probability value. Along with an assumption that costs are higher than predicted in the majority of cases, this empirical assessment of cost yields Fig. 2. There are no data to support numerical scales that could be a required aspect of future cost modeling activities. The discussion in this Note is to suggest a process for program managers to recognize the probable effects of maturity on the costs of technology.

Conclusions

Detailed definitions have been suggested for technology readiness levels from 1 through 7, the typical range for technology development. These definitions provide guidance on how to progress from one level to higher levels. It is suggested that the TRLs can provide formal exit criteria for tasks or phases in a technology development program. Risk is discussed as the inverse of the TRL progression. Last, the cost implications are discussed, but only in a qualitative manner.

Reference

[1] "Best Practices—Better Management of Technology Development Can Improve Weapon System Outcomes," Rept. GAO/NSIAD-99-162, U.S. General Accounting Office, Washington, DC, July 1999.

Errata

Strength of Stiffened 2024-T3 Aluminum Panels with Multiple Site Damage

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The eighth column in Table 1 should be labeled $2t_s$ rather than t_s.