Technology Readiness Levels Adapted for Use in IM Development

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Executive Summary

The author was tasked in 2014 by the manager of the Joint Insensitive Munitions Technology Program (JIMTP) to develop Technology Readiness Levels (TRLs) that would be more appropriate to IM development activities than those that were then currently in use. TRL definitions codified in US Department of Defense instructions were generally most applicable to weapon systems rather than weapon components. In JIMTP, development activities range from the characterization and scale-up of new energetic molecules, through the development of new propellant or explosive formulations and mitigation devices, to the incorporation of these new technologies into weapon components. In addition, a measure of program success for JIMTP has been the advancement of a technology to a higher TRL. Applied research needs to be developed to TRL 4-5 and transition to advanced technology demonstrations which will then take the technology up to TRL 6-7. Using the older, system-level definitions provided limited and inconsistent guidance to project principal investigators as well as to JIMTP management. The system engineer can argue that a well characterized component is nothing more than a component, and until it is utilized in a subsystem, there is no TRL at all. Conversely, the chemist or materials engineer can say that his new compound or material is completely characterized and manufactured at the ton level and is clearly mature, meaning a high TRL level. The JIMTP TRL definitions attempt to take both of these views into account and provide a means of gauging the maturity of a proposed technology and assessing the risk.

Background – The Joint Insensitive Munitions Technology Program

The Director for Land Warfare and Munitions in the Office of the Assistant Secretary Of Defense for Acquisition, Technology and Logistics established the Joint Insensitive Munitions Technology Program (JIMTP) in 2008 to develop a Science and Technology base to support the Secretary of Defense in ensuring that United States (US) munitions under development or procurement are safe to the maximum extent practicable throughout their lifecycle when subjected to unplanned stimuli. These enabling technologies could then be used by the Services as they develop their specific weapon systems.

Counteracting the IM threats is a complex task that requires extensive planning. There are a significant number of US weapon systems that require IM signature improvements, and too little is currently known about the weapon design factors that influence the reaction severity. To help bound the problem, JIMTP divides up all the weapon systems into five areas, called Mission Area Technology Groups (MATGs). Each is managed by a Lead, with help from two Co-leads from the other two Military Services. The current IM status of each high priority weapon system and the related technology development needs to achieve IM compliance are documented by the program managers biennially. These are then used by the MATGs to create or modify a series of goals which can be flowed down to component objectives for the propellant or explosive, for a mitigation system, or for the motor, gun propellant or warhead itself. These are then turned in to technology gaps which can be used by US industry, the Department of Defense (DoD) laboratories and the Department of Energy laboratories to develop and propose solutions. These proposals, in the form of white papers, are due each December. The JIMTP leadership selects best new ideas for full proposals which are then due in May. All new and continuing project plans are then evaluated, and the most promising that can be selected with the available funding become the JIMTP program for the following year.

These proposals are evaluated and selected based on the potential for IM improvement, the current maturity of the technology (based on the Technology Readiness Level or TRL), the soundness of the technical approach, the relevance to the MATG roadmaps and goals and the transition potential.

The progress and success of the JIMTP is judged by the transitions of developed technology to weapon programs, but also by the advancement of technology to the next level of development. In order for a technology to be deemed ready for inclusion in a weapon system, it must be at a minimum of TRL 6 in accordance with DoD regulations. (The TRL definitions will come later in the paper.) New ideas proposed to JIMTP generally need to be at TRL 2 to 3. A JIMTP Applied Technology (6.2 level) project is designed to move the TRL to 4 to 5, where it would be funded in an Advanced Technology Demonstration (6.3 level) project. This would bring the technology up to TRL 6 or 7. Note, however, that the failure to achieve the intended goals of a project, to transition to a program, or to advance to the appropriate TRL can also be considered a success if it advances the fundamental understanding of materials or the science.

IM "solutions" must be at the system level, and are usually system specific. One size or technology does not fit all. But, JIMTP is focused on incrementally improving the IM responses, not necessarily in achieving IM compliance in the short term. And, JIMTP works at the weapon component level – the rocket motor, the gun propellant, the warhead. IM improvements are made by modifying the energetic and/or non-energetic material ingredients and structures of these weapon components or adding mitigation systems such as venting and ballistic protection and by design modifications. In addition, the development of enabling technologies such as modeling and simulation and sub-scale tests is required.

Technology Readiness Levels

As already noted, in JIMTP the maturity of a technology is evaluated upon the receipt of a new idea and at various times as the project goes forward. And, the parts that make up the technology may be at different levels of maturity. For example, a new ingredient may be readily available and have known properties. It may also be already fielded in a weapon system. It could be at a TRL of 9. However, the new technology may be a propellant containing that ingredient and that propellant could just be a concept with only hand mixes conducted. It may then be at a TRL of 2. The propellant could go into the production motor case (TRL of 9), but a mitigation device known to work on other motors could be added (TRL of 6). What, then, would be the overall TRL of the technology? How should it be defined? How should the TRL of each of the pieces be defined?

Technology Readiness Level (TRL) is standard terminology, but it was not applied in a standard manner. Several years ago, a fellow propulsion engineer noted, "TRL definitions were developed as a communication tool. They can be very useful – if well defined. The problem in all communication is that the recipient often receives a different message than what the sender thought he sent. So it is important to have as many people on the same page with respect to definitions as possible, minimizing differences in understanding and establishing a meaningful reference for additional discussion."[i]

The TRL concept dates back many years, most believe to NASA in the mid-1970s[ii] where it was used to assess the technology readiness of a spacecraft design. At the time, there were only the seven levels shown in Table I. The Air Force and more of NASA picked up on the concept, and within a decade, the TRL definitions we are most familiar with were considered standard, with a few variations. The NASA definitions are shown in Table II[iii] and the DoD definitions in Table III[iv].

Table I. Original NASA TRL Definitions

Level 1	Basic Principles Observed and Reported
Level 2	Potential Application Validated
Level 3	Proof-of-Concept Demonstrated, Analytically and/or Experimentally
Level 4	Component and/or Breadboard Laboratory Validated
Level 5	Component and/or Breadboard Validated in Simulated or Real space Environment
Level 6	System Adequacy Validated in Simulated Environment
Level 7	System Adequacy Validated in Space

Table II. Current NASA TRL Definitions

Technology Readiness Level	Description
1. Basic principles observed and reported	This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development.
2. Technology concept and/or application formulated	Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
3. Analytical and experimental critical function and/or characteristic proof of concept	At this step in the maturation process, active research and development (R&D) 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.
4. Component and/or breadboard validation in laboratory environment	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5. Component and/or breadboard validation in relevant environment	At this level, the fidelity of the component and/or breadboard being tested has to increase 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.
6. System/subsystem model or prototype demonstration in a relevant environment (ground or space)	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 breadboarding - would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space.
7. System prototype demonstration in a space environment	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in space.
8. Actual system completed and 'flight qualified' through test and demonstration (ground or space)	In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system.
9. Actual system 'flight proven' through successful mission operations	In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. This might include integration of new technology into an existing system. This TRL does *not* include planned product improvement of ongoing or reusable systems.

Table III. Current DoD TRL Definitions

Technology readiness level	Description	Supporting information
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology’s basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
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	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and

	fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?

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 (OT&E). Examples include using the system under operational mission conditions.	OT&E (operational test and evaluation) reports.

As can be seen from the definitions, the concept was devised for essentially large-scale systems. However, over the years, these same definitions have been applied to everything from new ingredients, to formulations, to rocket motors and warheads, to full missile systems and to systems of systems.

TRL Evolution

In order to make the definitions for relevant, various changes have been proposed. The DoD Technology Readiness Assessment (TRA) Deskbook from 2005 had definitions, descriptions and supporting information for hardware, for software and for manufacturing technology. Rich Bowen and Ken Tomasello of the Navy Insensitive Munitions Office proposed "Technology Readiness Levels for Insensitive Munitions Programs" in 2007[v], noting that "there seems to be some discrepancy between the services in Technology Readiness Level (TRL) definition. One reason for this is that there is not a clear cut TRL definition established for Insensitive Munition technology development. Rich Bowen and I have developed TRLs specifically for IM Technology development which I have included as an enclosure. I would appreciate it if you could look over the TRL list for IM and comment back to me with your thoughts. I plan to get a Navy consensus and then put this forward to all of the services for a joint review and hopefully consensus. I think that it is important to establish the IMAD and IMTTP steps in the TRL process. I have also included a thermometer chart for quick reference of the TRL levels. We gathered all of the known TRL level definitions from DOD, NASA and ONR and then used those as the reference in developing the enclosed TRL definitions for IM Technology." Also in 2007, Chris Michienzi, then of the Naval Surface Warfare Center Indian Head Division and soon after a JIMTP MATG Lead, proposed Technology Readiness Levels of Propellants. This was in reference to gun propellants. David Dean, mentioned earlier, also proposed "Component Readiness Levels." In 2008, the Propulsion Integrated Project Team (IPT) put together by the sponsor of the JIMTP, but a few years prior, came out with the recommendation to "Establish criteria for technology and manufacturing readiness levels." This led to a workshop at a meeting of the Joint Army-Navy-NASA-Air Force Interagency Propulsion Committee (JANNAF) where options were discussed. In 2010, Bossard and Rhys published an AIAA paper entitled, "Propellant Readiness Level: A Methodological Approach to Propellant Characterization".[vi] And that brings us to 2014.

<u>The JIMTP Technology Readiness Levels</u>

The author was tasked in 2014 by the JIMTP Program Manager to develop Technology Readiness Levels that would be more appropriate to IM development activities than those that were then currently in use. Since I had been involved in some of the earlier activities, a draft was based on what had come before, adjusting values based upon my own judgment. This draft was presented at the JIMTP Strategic Planning Meeting in June 2014, and a small team of MATG leads and co-leads was established to refine the definitions to ensure they would fit all JIMTP technology types. This was finalized prior to the annual Technical Advisory Committee meeting in August and incorporated into the JIMTP Strategic Plan. These definitions are shown in Table IV. Each level for each step is tied to milestones that would be common to the development of ingredients, of gun or rocket propellants, of explosives, of mitigation systems or of rocket motors or warheads. The reader might quibble about the exact values, and all comments and feedback are welcomed. However, the idea was to establish common definitions for JIMTP, not absolute definitions. So, please don't quibble too much.

Table IV. JIMTP TRL Definitions

TRL	Ingredient	Formulation	Mitigation Device	Weapon Subsystem
1. Basic principles Observed and Reported (6.1)	Fundamental research to develop new ingredient concepts. Technical publication or report reviewed and recognized by the technical community.	Formulation(s) conceived using literature search of ingredients and their properties.	Design/concept studies of a technology's basic properties. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Identification of available component technologies, design/trade studies and analysis of approaches.
2. Technology concept and/or application formulated (6.1/6.2)	Ingredients synthesized and produced at 5 gram level. Safety characterization tests	Thermochemical calculations performed (Cheetah, PEP, etc.). First mixes (hand or mechanical): thermal and mechanical sensitivity/safety data, ingredient compatibility/solubility, demonstrate processing and cure.	Early laboratory studies to physically validate analytical predictions. Parts are not yet integrated or representative.	Concept development. Component studies. Theoretical performance analyses. Bench-top testing.
3. Analytical and experimental critical function and/or characteristic proof of concept (6.2)	Synthesis is optimized at laboratory level to ~50 gram level. Material is completely characterized and the synthesis yields consistent results at this scale.	Mixes up to 1lb: experiment with formulation, determine processability, burning rate (strand burn, closed bomb), mechanical properties, small-scale vulnerability testing to test thermal and/or impact response.	Parts are integrated to establish that they will work together in the device. Bench-top testing.	Components selected. Fabrication and integration begins.
4. Component validation in pilot plant,	Scale-up begins. Quantities of	Mixes to 10lb: formulation refined/optimized,	Realistic components are integrated.	Sub-scale, analog and/or surrogate

laboratory or simulated environment (6.2/6.3)	reproducible material are available and sufficient for 6.2-level formulation efforts.	repeat testing from TRL3. Sub-scale performance testing. Consistent mix quality and performance results.	Device tested in a simulated environment.	testing to validate IM and performance.
5. Component validated in relevant environment (6.3)	Scale-up is demonstrated. Quantities of reproducible material are available and sufficient for 6.3-level formulation efforts.	Mixes to 50 lb with pilot plant grade ingredients. Formulations evaluated at full scale. Large scale testing is initiated.	Fabrication and testing of the device on sub-scale weapon components to validate performance.	Full-scale fabrication and testing begins, often with some simulated components.

Concluding Remarks

The system engineer can argue that a well characterized component is nothing more than a component, and until it is utilized in a subsystem, there is no TRL at all. Conversely, the chemist or materials engineer can say that his new compound or material is completely characterized and manufactured at the ton level and is clearly mature, meaning some high TRL level. The JIMTP TRL definitions attempt to take both of these views into account and provide a means of gauging the maturity of a proposed technology and assessing the risk.

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[i] Dean, David, Naval Air Warfare Center Weapons Division. Email to Stuart Blashill, 2007.

[ii] Banke, Jim, NASA; "Technology Readiness Levels Demystified", 2010.

[iii] Mankins, John C. (6 April 1995). "Technology Readiness Levels: A White Paper". NASA, Office of Space Access and Technology, Advanced Concepts Office.

[iv] "Technology Readiness Assessment (TRA) Guidance". United States Department of Defense. April 2011

[v] Tomasello, Ken, Navy Insensitive Munitions Office. Email to Navy IM S&T Scientists. February 2007.

[vi] Bossard and Rhys. “Propellant Readiness Level: A Methodological Approach to Propellant Characterization” – AIAA 2010-6732, 2010.