

TRL Assessment Methods

Entry #:	18.40.4
Word Count:	13240 words
Reading Time:	66 minutes
Last Updated:	September 16, 2025

"In space, no one can hear you think."

Table of Contents

Contents

1	TRL Assessment Methods	2
1.1	Introduction to TRL Assessment Methods	2
1.2	Historical Development of TRL Assessment	4
1.3	The TRL Scale: Definition and Structure	8
1.4	Methodologies for TRL Assessment	13
1.5	Application in Different Industries	18
1.6	TRL Assessment in Government and Defense	19
1.7	TRL Assessment in Commercial Innovation	25

1 TRL Assessment Methods

1.1 Introduction to TRL Assessment Methods

Technology Readiness Level (TRL) assessment stands as one of the most influential yet often underappreciated frameworks in modern technology management and innovation. At its core, TRL provides a structured, universally understood language for quantifying the maturity of a technology as it progresses from a mere concept to a fully operational system. This systematic measurement system, typically represented as a scale from 1 (basic principles observed) to 9 (actual system proven in operational environments), serves as a vital navigational tool through the complex and often perilous journey of technological development. Before the advent of such formalized assessment methods, technology maturation was frequently characterized by subjective judgments, unrealistic timelines, costly surprises, and project failures stemming from premature deployment or inadequate preparation. The genesis of TRL assessment emerged directly from these pain points, particularly within high-stakes environments like aerospace and defense, where the consequences of misjudging technology maturity could be measured not just in financial losses, but in mission failure and even human life. The framework was conceived as a response to the perennial challenge of answering deceptively simple yet critically important questions: How mature is this technology, really? Is it ready for the next phase of development? Can it be reliably integrated into a larger system? And crucially, when can stakeholders realistically expect it to perform as intended under operational conditions? By providing clear, evidence-based definitions for each stage of maturity, TRL assessment transforms these abstract inquiries into concrete, measurable milestones, fostering transparency and shared understanding among diverse technical and non-technical stakeholders. It establishes a common lexicon that bridges communication gaps between scientists, engineers, program managers, investors, and policymakers, enabling more informed and coordinated decision-making throughout the technology lifecycle. This foundational concept of a standardized maturity scale has proven remarkably versatile, adapting far beyond its origins to serve as a cornerstone of technology evaluation across an astonishingly diverse array of sectors and disciplines.

The significance of TRL assessment in technology management and decision-making cannot be overstated. In an era characterized by rapid technological change and intense competition for resources, organizations face constant pressure to make strategic choices about which technologies to fund, develop, integrate, or abandon. TRL assessments provide the critical evidence base needed to navigate these high-stakes decisions effectively. They inform resource allocation by identifying technologies that have reached sufficient maturity to warrant significant investment, while also highlighting those requiring further foundational research before substantial funding is justified. For instance, a government agency might use TRL assessments to prioritize research grants, channeling funds toward projects at TRL 3-4 that have demonstrated proof of concept but need validation, while deferring support for concepts still at TRL 1-2 until basic principles are more firmly established. Conversely, venture capitalists might focus investments on technologies at TRL 5-6, where laboratory validation has occurred but market-ready prototypes need development. Beyond funding, TRL is indispensable for risk management. Each leap between levels represents a significant step forward but also introduces new uncertainties. A technology moving from TRL 4 (lab validation) to TRL 5 (relevant environment testing) faces the formidable challenge of performing outside controlled laboratory conditions,

while the jump from TRL 6 (prototype in relevant environment) to TRL 7 (operational prototype) demands integration into realistic operational contexts. By explicitly defining these transitions, TRL allows managers to anticipate potential failure points, develop mitigation strategies, and allocate contingency resources appropriately. The framework also creates invaluable transparency in technology progression. It replaces vague assertions like “we’re making good progress” or “it’s almost ready” with specific, auditable maturity levels. This clarity is essential for establishing realistic expectations and timelines. A project manager can confidently state that a system is at TRL 7, meaning an operational prototype has been demonstrated, but qualification and operational testing (TRL 8-9) typically require 18-24 months, preventing premature promises of deployment. This transparency builds trust among stakeholders and underpins more accurate planning and forecasting. The Joint Strike Fighter (F-35) program, for example, learned hard lessons about TRL management when key technologies were not sufficiently mature (below TRL 6) at the program’s critical design review in the early 2000s, contributing to significant cost overruns and schedule delays – a stark illustration of the consequences of ignoring TRL guidance.

The scope and applicability of TRL assessment extend far beyond the aerospace and defense sectors where it first took root. While NASA and the Department of Defense pioneered its use, the fundamental principles of systematically measuring technology maturity have proven universally relevant. Today, TRL frameworks are actively employed across a remarkably broad spectrum of domains, including energy (both renewable and conventional), healthcare and biotechnology, information and communication technology, transportation, manufacturing, and even agriculture. In the energy sector, organizations like the U.S. Department of Energy utilize TRL assessments to guide investments in technologies ranging from advanced battery storage systems (TRL 3-4 for novel chemistries) to next-generation nuclear reactors (TRL 5-7 for demonstration plants). The healthcare industry has adapted TRL for medical device development, pharmaceutical research, and diagnostic tools, often integrating it with regulatory pathways like those defined by the Food and Drug Administration (FDA). A novel cancer diagnostic platform might progress from TRL 1 (identification of biomarkers) through TRL 5 (laboratory prototype validation) to TRL 8 (system completion and qualification for clinical trials) before reaching TRL 9 (proven in routine clinical use). The information technology sector presents unique challenges due to the rapid pace of software development and iterative methodologies like Agile. Nevertheless, TRL assessments are increasingly applied, sometimes with adaptations, to evaluate everything from artificial intelligence algorithms (TRL 2-3 for initial concept validation) to complex enterprise software systems (TRL 7-9 for deployment in operational environments). The versatility of TRL extends to both hardware and software technologies, though the specific evidence requirements and assessment methodologies differ significantly. Hardware TRL assessment often relies heavily on physical prototypes, environmental testing, and performance metrics, while software assessment emphasizes functional validation, integration testing, user acceptance, and cybersecurity verification. Furthermore, TRL frameworks demonstrate remarkable adaptability to varying application complexity and stakeholder requirements. A simple sensor technology might require a relatively straightforward TRL assessment, while a complex system-of-systems like a smart city infrastructure demands a more nuanced, multi-layered TRL evaluation that considers the maturity of individual components, their integration, and the overall system functionality. This flexibility allows organizations to calibrate the rigor and detail of their TRL assessments to match the

specific risks, costs, and strategic importance of the technology in question, ensuring the framework remains practical and valuable across countless technological contexts.

The effective implementation of TRL assessment involves a diverse ecosystem of stakeholders, each bringing distinct perspectives, requirements, and expectations to the process. Government agencies represent perhaps the most prominent and influential users of TRL frameworks. For bodies like NASA, the Department of Defense, the Department of Energy, and their international counterparts (such as the European Space Agency or the UK's Defence Science and Technology Laboratory), TRL assessments are integral to acquisition processes, program management, and accountability to taxpayers and oversight bodies. These agencies typically require high levels of assessment rigor, detailed documentation, and often mandate specific TRL thresholds that technologies must achieve before critical program milestones, such as passing preliminary design review or entering full-scale development. Research institutions, including universities and national laboratories, utilize TRL assessments primarily to guide internal research priorities, secure funding, and facilitate technology transfer to industry. Their perspective often focuses on bridging the notorious "valley of death" between fundamental research (TRL 1-3) and commercial application (TRL 7-9), using TRL as a tool to identify promising technologies requiring further development support. Private sector companies, ranging from large multinational corporations to nimble startups, employ TRL assessments with varying degrees of formality depending on their size, industry, and corporate culture. Large industrial firms, particularly in aerospace, defense, and energy, often have sophisticated internal TRL processes aligned with government standards to manage their R&D portfolios and ensure technologies meet customer requirements. Startups and smaller companies may use less formal TRL evaluations to track progress, communicate status to investors, and plan development roadmaps. Investors, including venture capitalists, private equity firms, and corporate venture arms, represent another crucial stakeholder group. They leverage TRL assessments as part of their due diligence process, using maturity levels to gauge technical risk, estimate time to market, and inform valuation models. An investor might view a technology at TRL 4 as having significant potential but requiring substantial capital and time to reach commercial viability, whereas a technology at TRL 7 might be seen as nearing market entry with a clearer path to revenue. The varying needs of these stakeholders profoundly shape assessment methodologies and reporting requirements. A government contract might demand a comprehensive TRL assessment report with extensive evidence documentation and expert validation, while an internal corporate review might rely on a simpler checklist and team consensus. Understanding these stakeholder perspectives is essential for designing TRL assessment processes that deliver meaningful, actionable insights tailored to the specific decision-making context. This intricate interplay of stakeholder needs, technological diversity, and methodological adaptation underscores the dynamic and multifaceted nature of TRL assessment as a discipline, setting the stage for exploring its historical evolution and detailed structural frameworks in the sections that follow.

1.2 Historical Development of TRL Assessment

The historical development of Technology Readiness Level assessment represents a fascinating journey from pragmatic problem-solving within NASA to global standardization across industries. This evolution reflects

both the universal challenges of technology maturation and the iterative process of refining management tools through practical application and shared learning. While Section 1 established the fundamental concepts and broad relevance of TRL, examining its origins reveals how specific historical pressures and visionary individuals shaped a tool that would eventually transform technology management worldwide.

The origins of TRL assessment are deeply rooted in the crucible of NASA's technological ambitions and budgetary realities during the 1970s and 1980s. Following the triumphs of the Apollo program, NASA faced a new era of constrained budgets alongside increasingly complex technological demands for projects like the Space Shuttle and proposed space stations. Within this context, the agency grappled with persistent challenges in technology management: overly optimistic promises about technology readiness, unexpected integration failures, costly project delays, and difficulties in communicating technology status to decision-makers. It was against this backdrop that Stan Sadin, a NASA Headquarters manager in the Office of Advanced Concepts and Technology, began developing a more structured approach to technology assessment in the mid-1970s. Sadin recognized that NASA needed a systematic method to answer a critical question: "Is this technology ready for incorporation into a flight system?" His initial work, though informal, established the core concept of defining discrete stages of technology maturity based on demonstrated evidence. This early framework provided a foundation, but it was John Mankins, who joined NASA in the late 1980s and later managed the Advanced Concepts Studies program, who would significantly refine and formalize Sadin's ideas. Mankins expanded the concept into a more comprehensive scale, explicitly defining the progression from basic research to operational deployment. His work culminated in NASA's first formal TRL white paper in 1995, which codified the now-familiar nine-level scale and provided detailed definitions for each stage. This document, though initially an internal NASA publication, marked the birth of the modern TRL framework. The Space Race context was crucial to this development; the high stakes of space exploration, where technology failures could mean mission loss and even astronaut fatalities, created an environment demanding rigorous technology management. Furthermore, NASA's unique position as a government R&D agency bridging fundamental research and operational systems necessitated a tool that could span this entire spectrum. Early applications within NASA focused on spacecraft components like advanced propulsion systems, life support technologies, and communication arrays, where the consequences of immature technology were particularly severe. The Space Shuttle program, for instance, experienced numerous technical challenges that underscored the need for better technology readiness assessment, including issues with thermal protection tiles and main engine performance that might have been mitigated with more rigorous pre-development evaluation.

From its NASA origins, TRL assessment began a deliberate spread across other U.S. government agencies throughout the 1990s, driven by common challenges in technology management and increasing pressure for accountability in public spending. The Department of Defense emerged as the earliest and most significant adopter beyond NASA, facing analogous pressures in developing increasingly complex weapon systems within constrained budgets. The end of the Cold War brought significant defense budget reductions while simultaneously accelerating technological change, creating a perfect storm for technology management challenges. Programs like the F-22 Raptor and Comanche helicopter encountered difficulties stemming from integrating immature technologies, highlighting the need for better assessment tools. The DoD's

formal embrace of TRL began in earnest in the mid-1990s, with the Air Force Research Laboratory and Defense Advanced Research Projects Agency (DARPA) among the early adopters. These agencies recognized that TRL provided a common language to evaluate technologies across diverse programs and communicate readiness levels to acquisition decision-makers. A pivotal moment came in 1995 with the publication of the “DoD Technology Readiness Assessment Deskbook,” which adapted NASA’s TRL framework for defense applications. This document, developed under the leadership of individuals like Raymond Colladay, who had previously served as NASA’s Associate Administrator for Aeronautics and Space Technology, represented the first major systematic adaptation of TRL outside its original context. The DoD version maintained the core nine-level structure but refined definitions to reflect defense-specific technologies and acquisition processes. For instance, TRL 6 was redefined to emphasize demonstration in a “relevant environment” that might include electromagnetic interference testing critical for military systems. The Navy and Army quickly developed their own implementing guidance, while DARPA employed TRL assessments to manage its high-risk, high-reward technology portfolio, using maturity levels as gates for continued funding. Several factors facilitated this rapid adoption across government. First, the Government Performance and Results Act of 1993 required federal agencies to demonstrate the effectiveness of their R&D investments, creating pressure for more rigorous technology evaluation. Second, the increasing complexity and cost of defense systems made technology integration risks more apparent and costly. Third, the success of early adopters provided compelling case studies; for example, the Joint Direct Attack Munition (JDAM) program benefited from applying TRL assessments to its GPS guidance technology, helping to ensure that key components were sufficiently mature before full-scale production. By the late 1990s, TRL had become sufficiently ingrained in DoD processes that it was formally incorporated into the Defense Acquisition Guidebook, establishing it as a required element of technology development planning and review across the department.

The international diffusion of TRL assessment followed a pattern similar to its spread within the U.S. government, beginning with space agencies and gradually expanding to other sectors as its utility became apparent. The European Space Agency (ESA) emerged as one of the earliest international adopters, facing similar challenges to NASA in managing complex space technology development across multiple European nations. ESA began experimenting with TRL concepts in the mid-1990s, formally adopting a nine-level scale based on NASA’s framework in 1998. However, the European implementation was not merely a copy of the American model; ESA adapted the definitions to reflect its specific organizational structure and technology development processes, placing greater emphasis on technology verification and validation procedures consistent with European engineering standards. This adaptation process illustrates how TRL frameworks maintain core principles while flexing to accommodate different institutional contexts. The successful implementation within ESA spurred adoption by other European space agencies and organizations, including the French Centre National d’Études Spatiales (CNES), the German Aerospace Center (DLR), and the UK Space Agency. By the early 2000s, TRL had become sufficiently established in European space activities that it was incorporated into the European Cooperation for Space Standardization (ECSS) engineering standards, specifically in ECSS-E-ST-10-02C “Space engineering – Technology readiness levels,” published in 2008 and subsequently updated. This standardization effort represented a significant milestone in TRL’s evolution, moving the framework beyond individual agency practices to formalized international standards.

Beyond Europe, other spacefaring nations including Japan (JAXA), India (ISRO), and Canada (CSA) developed their own TRL implementations, often drawing from both NASA and ESA models while tailoring them to national priorities and capabilities. The diffusion extended beyond space agencies to international organizations involved in technology development and cooperation. NATO, for instance, developed its own TRL framework to facilitate technology collaboration among member nations, recognizing that a common maturity scale was essential for joint development programs. The Organization for Economic Co-operation and Development (OECD) also began promoting TRL concepts as part of its work on innovation policy, particularly for evaluating public research investments. A particularly significant development in international standardization came in 2013 when the International Organization for Standardization (ISO) published ISO 16290:2013 “Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria assessment.” This ISO standard, developed collaboratively by experts from NASA, ESA, and other national space agencies, represented the first truly global consensus on TRL definitions and assessment criteria, cementing the framework’s status as an international best practice. The international journey of TRL assessment demonstrates how a practical management tool developed to address specific challenges within one organization can evolve into a global standard through recognition of its universal value and adaptation to diverse contexts.

The evolution of TRL assessment from a simple nine-level scale to a comprehensive framework represents perhaps the most significant aspect of its historical development, reflecting both technological change and accumulated experience in technology management. The original NASA white paper of 1995, while groundbreaking, presented a relatively straightforward scale with basic definitions for each level. However, as organizations gained experience applying TRL assessments, they recognized the need for more detailed guidance, particularly regarding the evidence required to demonstrate achievement of each level and the assessment process itself. This led to the development of increasingly sophisticated implementation handbooks and guidance documents. NASA itself produced several revisions to its TRL documentation, including a significantly expanded version in 2002 that provided more detailed criteria for each level and addressed common assessment challenges. Similarly, the DoD continuously updated its TRL deskbook, with the 2009 version incorporating lessons learned from a decade of implementation across defense programs. A key aspect of this evolution was the recognition that TRL assessments needed to be supported by robust evidence and consistent methodologies. Early implementations sometimes suffered from “TRL inflation,” where programs claimed higher maturity levels than warranted due to subjective interpretations or pressure to demonstrate progress. To address this, organizations developed more rigorous assessment processes, including structured evidence requirements and independent validation procedures. For example, NASA’s Innovative Partnerships Program implemented a formal Technology Readiness Assessment process requiring documented evidence for each TRL criterion and independent review by subject matter experts. Another important evolution was the integration of TRL with complementary assessment tools and frameworks. Practitioners recognized that while TRL effectively measured technical maturity, it needed to be combined with other dimensions to provide a complete picture of technology viability. This led to the development of integrated assessment approaches that incorporated Manufacturing Readiness Levels (MRL) to evaluate production maturity, Integration Readiness Levels (IRL) to assess system compatibility, and Software Readiness Levels (SRL) for

software-intensive systems. The Department of Energy, for instance, developed an integrated assessment framework that combined TRL with market readiness assessments to evaluate both technical and commercial viability of energy technologies. Technological changes themselves influenced TRL's evolution. The rise of software-intensive systems, model-based engineering, and digital twins prompted refinements in how TRL criteria were applied to non-hardware technologies. NASA's 2015 TRL guidance, for example, included specific considerations for software and modeling technologies, recognizing that traditional hardware-focused definitions were insufficient for these increasingly important domains. Similarly, the rapid pace of development in fields like artificial intelligence and biotechnology led some organizations to develop specialized TRL variants or supplementary criteria to address unique aspects of these technologies. Perhaps the most significant evolution has been the shift from viewing TRL as a simple reporting metric to treating it as an integral part of a comprehensive technology management process. Modern implementations embed TRL assessments within broader technology maturation plans, using them to identify specific risks, guide resource allocation, and inform decision gates throughout the development lifecycle. This evolution from scale to comprehensive framework reflects the maturation of TRL assessment itself—from a useful concept to a sophisticated management discipline that continues to evolve in response to new challenges and contexts. This rich historical development sets the stage for examining the detailed structure and definitions of the modern TRL scale, which will be explored in the next section.

1.3 The TRL Scale: Definition and Structure

This rich historical development sets the stage for examining the detailed structure and definitions of the modern TRL scale, which has evolved from its simple origins into a sophisticated framework for technology assessment. The standard 9-level TRL scale represents one of the most widely adopted and recognized frameworks for measuring technology maturity across industries and organizations worldwide. At its core, the TRL scale provides a systematic progression from the most fundamental scientific observations to fully operational systems, with each level representing a distinct stage of maturity characterized by specific criteria and evidence requirements. The scale begins at TRL 1, where basic principles are first observed and reported, and culminates at TRL 9, where the actual system has been proven through successful mission operations in its intended environment. This progression is not arbitrary but reflects the natural lifecycle of technology development, moving from concept through validation to implementation. The nine levels are deliberately distributed to provide meaningful granularity while remaining practical for assessment purposes. Too few levels would result in overly broad categories that mask critical differences in maturity, while too many levels would create unnecessary complexity without adding significant value for decision-makers. The current structure strikes a balance that has proven effective across diverse technological domains, from aerospace components to software systems. The logical progression of the scale follows a technology's journey from laboratory to field, with the first three levels (1-3) encompassing basic research activities, the middle three (4-6) covering development and integration efforts, and the final three (7-9) addressing deployment and operational validation. This tripartite structure aligns with typical technology development phases and funding cycles, making the scale particularly useful for planning and resource allocation. The rationale behind the specific criteria at each level has been refined through decades of practical application, with definitions

evolved to address common assessment challenges and ambiguities. For instance, the distinction between laboratory and relevant environments (TRL 4 to TRL 5) and between relevant and operational environments (TRL 6 to TRL 7) reflects critical transition points where technologies often face significant technical risks and increased costs. The scale's design enables consistent communication about technology status across diverse stakeholders, from researchers to investors to program managers, creating a shared understanding that facilitates informed decision-making. This universal applicability, combined with its structured approach to evidence-based assessment, has established the 9-level TRL scale as a cornerstone of technology management worldwide.

The earliest stages of technology development, encompassed by TRL levels 1 through 3, represent the foundational research phase where scientific curiosity meets practical application. TRL 1, defined as “Basic principles observed and reported,” marks the very beginning of the technology journey. At this stage, researchers have identified and documented fundamental scientific principles or phenomena that could potentially form the basis of a future technology. The evidence required for TRL 1 typically includes peer-reviewed publications documenting observations, theoretical analyses, or initial experimental results that establish the scientific feasibility of the concept. It's important to note that TRL 1 does not imply any specific application; rather, it simply indicates that the underlying physics or scientific principles have been observed and documented. For example, the discovery of high-temperature superconductivity by Bednorz and Müller in 1986, which earned them the Nobel Prize in Physics, represented TRL 1 for this revolutionary technology. Their published observations of superconductivity at temperatures significantly higher than previously thought possible established the basic principle without yet envisioning specific applications. Assessment at TRL 1 relies heavily on scientific peer review and validation of the fundamental observations. The transition to TRL 2 occurs when “Technology concept and/or application formulated.” At this level, researchers have moved beyond merely observing principles to proposing practical applications based on those principles. The key advancement is the articulation of how the scientific phenomenon could be harnessed to solve a particular problem or meet a specific need. Evidence for TRL 2 typically includes application papers, concepts of operation, or analyses that outline how the technology might work in practice. For instance, following the discovery of high-temperature superconductivity, researchers began formulating concepts for applications such as more efficient power transmission systems, advanced medical imaging devices, or improved magnetic resonance imaging (MRI) machines. These formulations, documented in technical papers or preliminary design concepts, would qualify as TRL 2 achievements. Assessment at this stage focuses on the plausibility and potential feasibility of the proposed application, often involving expert review of the concept's scientific basis and practical viability. The progression to TRL 3, “Analytical and experimental critical function and/or characteristic proof of concept,” represents a significant step forward in technology maturation. Here, researchers have moved from concept to initial validation, demonstrating that the proposed technology can actually perform its critical functions under controlled conditions. This stage typically involves analytical studies, laboratory experiments, or breadboard models that validate the fundamental aspects of the technology concept. The evidence requirements become more rigorous at TRL 3, including experimental data, analytical results, or proof-of-concept demonstrations that show the technology can achieve its intended function. For example, in the development of CRISPR gene-editing technology, the initial demonstration

by Jennifer Doudna and Emmanuelle Charpentier that the CRISPR-Cas9 system could be programmed to cut specific DNA sequences represented a TRL 3 achievement. Their experiments, published in 2012, provided analytical and experimental proof that the concept could work as intended, even though the technology was far from being ready for practical applications. Assessment at TRL 3 involves evaluating whether the proof-of-concept demonstration adequately validates the critical functions of the technology and whether the results are sufficiently promising to warrant further development investment. This early research phase, spanning TRL 1 through 3, is characterized by high uncertainty but also high potential, as technologies at these stages represent the seeds of future innovation. The assessment methods for these levels emphasize scientific rigor, peer validation, and the establishment of credible evidence that the technology concept has merit and deserves further exploration.

As technologies progress beyond basic research, they enter the development phase encompassed by TRL levels 4 through 6, where concepts transform into tangible components and systems. TRL 4, defined as “Component and/or breadboard validation in laboratory environment,” marks the transition from proof-of-concept to initial integration and testing. At this stage, the technology has advanced beyond isolated experiments to components or breadboards that are tested together to demonstrate that they can work as a system. A breadboard is a low-fidelity representation of the technology that focuses on function rather than form, often constructed with commercial off-the-shelf components to quickly validate technical approaches. The evidence required for TRL 4 includes test data from laboratory demonstrations showing that the components can be integrated and that critical functions work as intended under controlled conditions. For example, in the development of lithium-ion battery technology, achieving TRL 4 would involve creating laboratory-scale battery cells using the proposed materials and chemistry, then testing them to validate performance characteristics like energy density, charge/discharge rates, and cycle life. Tesla’s early battery development work in the mid-2000s, which involved creating and testing various battery cell chemistries in laboratory settings, represented progression through TRL 4 as they validated fundamental performance characteristics before scaling up production. Assessment at TRL 4 focuses on whether the laboratory demonstrations sufficiently validate the technology’s functions and whether the integration of components works as expected. The advancement to TRL 5, “Component and/or breadboard validation in relevant environment,” represents a critical step as the technology moves from the controlled laboratory setting to conditions that more closely resemble its intended operational context. The key distinction between TRL 4 and TRL 5 is the environment: while TRL 4 testing occurs in ideal laboratory conditions, TRL 5 introduces environmental factors that the technology will face in real-world applications. These relevant environments might include temperature extremes, vibration, vacuum conditions, or other contextual factors depending on the technology’s intended use. Evidence for TRL 5 includes test data from demonstrations in these more realistic environments, showing that the technology can maintain its performance under these conditions. For instance, in the development of solar cells for space applications, TRL 5 would involve testing prototype solar cells not just in laboratory conditions but also in environments that simulate space conditions, including vacuum, thermal cycling, and radiation exposure. NASA’s testing of next-generation solar cell technologies in thermal vacuum chambers that replicate the space environment represents a classic TRL 5 activity, validating that the technology can perform in conditions relevant to its intended application. Assessment at TRL 5

emphasizes how well the technology performs under these more challenging conditions and whether any environmental factors significantly impact its functionality. The progression to TRL 6, “System/subsystem model or prototype demonstration in relevant environment,” marks another significant advancement as the technology matures from component-level validation to system-level integration. At this stage, the technology has progressed beyond breadboards to more realistic prototypes or models that represent the actual system in form, fit, and function. These prototypes are demonstrated in relevant environments to show that the system as a whole can perform its intended functions. The evidence required for TRL 6 includes test data from system-level demonstrations in relevant environments, showing that all components work together as intended. For example, in the development of autonomous vehicle technology, achieving TRL 6 would involve creating a prototype vehicle equipped with the proposed sensors, computing systems, and control algorithms, then testing it in realistic driving environments such as test tracks or controlled road conditions. Waymo’s early self-driving car prototypes, which were tested on closed courses and later on public roads with safety drivers, represented progression through TRL 6 as they demonstrated system-level functionality in relevant environments. Assessment at TRL 6 focuses on whether the prototype adequately represents the final system, whether all critical functions work together as intended, and whether the system demonstrates adequate performance in relevant environments. This development phase, spanning TRL 4 through 6, is characterized by increasing integration, realism, and environmental relevance as technologies progress from laboratory concepts to functional prototypes. The assessment methods for these levels emphasize rigorous testing, validation of system integration, and demonstration of performance in increasingly realistic conditions, providing the evidence needed to make informed decisions about further investment in the technology.

The final stages of technology development, encompassed by TRL levels 7 through 9, represent the transition from prototype to operational system, where technologies must prove they can perform reliably in their intended environments. TRL 7, defined as “System prototype demonstration in an operational environment,” marks a critical milestone as the technology moves from relevant testing to actual operational conditions. At this stage, a system prototype that closely resembles the final product is demonstrated in the environment where it will ultimately be used. The key distinction between TRL 6 and TRL 7 is the environment: while TRL 6 involves testing in relevant but simulated conditions, TRL 7 requires demonstration in the actual operational environment. This transition is particularly significant because technologies often encounter unforeseen challenges when moving from test environments to real-world operational contexts. Evidence for TRL 7 includes test data from demonstrations in operational environments, showing that the prototype system can perform its intended functions under realistic conditions. For example, in the development of weather forecasting satellites, achieving TRL 7 would involve launching a prototype satellite into orbit and demonstrating that it can collect and transmit weather data as intended. The Joint Polar Satellite System (JPSS-1), launched in 2017, represented a TRL 7 achievement as it was demonstrated in its operational environment of space, collecting atmospheric data that matched the performance requirements before being declared fully operational. Assessment at TRL 7 focuses on whether the prototype performs adequately in the operational environment, whether any unforeseen challenges emerge, and whether the system demonstrates sufficient reliability for further development. The advancement to TRL 8, “Actual system completed and qualified through test and demonstration,” represents the culmination of the development process as

the technology reaches its final form and undergoes rigorous qualification testing. At this stage, the actual system (as opposed to a prototype) has been completed and has undergone comprehensive testing to demonstrate that it meets all requirements and specifications. This qualification process typically includes extensive testing under various conditions, verification of all functions, and validation that the system meets performance, reliability, and safety requirements. Evidence for TRL 8 includes qualification test reports, verification and validation documentation, and certification that the system meets all specified requirements. For instance, in the development of commercial aircraft, achieving TRL 8 would involve completing the actual aircraft design and conducting exhaustive testing including ground tests, flight tests, and certification testing to demonstrate compliance with airworthiness standards. The Boeing 787 Dreamliner achieved TRL 8 in 2011 after completing its flight test program and receiving type certification from the Federal Aviation Administration, demonstrating that the actual system met all requirements for operational use. Assessment at TRL 8 emphasizes comprehensive verification that the system meets all specifications, that it performs reliably under all expected conditions, and that it is ready for operational deployment. The progression to TRL 9, “Actual system proven through successful mission operations,” represents the final stage of technology maturity, where the system has been successfully deployed and operated in its intended environment. At this stage, the technology has moved beyond qualification to actual operational use, demonstrating its reliability and effectiveness through successful mission operations. The key distinction between TRL 8 and TRL 9 is operational experience: while TRL 8 demonstrates that the system is qualified and ready for operation, TRL 9 provides evidence that it actually performs successfully in real-world operations over time. Evidence for TRL 9 includes operational performance data, mission success reports, and documentation of sustained operational capability. For example, in the development of Mars rovers, achieving TRL 9 would involve successfully landing and operating the rover on Mars, demonstrating that it can perform its scientific mission in the harsh Martian environment. NASA’s Curiosity rover, which landed on Mars in 2012 and has been conducting scientific operations for over a decade, represents a clear TRL 9 achievement, having proven its capabilities through years of successful mission operations on the Red Planet. Assessment at TRL 9 focuses on operational performance, reliability over time, and successful achievement of mission objectives in the actual operational environment. This deployment phase, spanning TRL 7 through 9, is characterized by increasing realism, completeness, and operational validation as technologies progress from prototypes to qualified systems to proven operational capabilities. The assessment methods for these levels emphasize operational testing, qualification verification, and validation through actual use, providing the evidence needed to confirm that the technology is mature and reliable for its intended application.

While the standard 9-level TRL scale has proven remarkably effective across diverse technological domains, various organizations have developed extended scales and variations to address specific needs and contexts. These extensions typically involve either adding levels below TRL 1 or above TRL 9, or modifying the standard scale to better accommodate particular types of technologies or development processes. The concept of TRL 0 has emerged in some frameworks to address the earliest stages of research, before even basic principles have been observed and reported. TRL 0 is sometimes defined as “Basic scientific research” or “Ideation and concept generation,” representing activities such as theoretical exploration, literature reviews, or brainstorming that precede the identification of specific technological principles. For example, research

into fundamental physics that might eventually lead to new energy technologies could be classified as TRL 0, as it represents the scientific foundation that could later yield observable phenomena (TRL 1) and technological concepts (TRL 2). The European Space Agency has incorporated TRL 0 in some of its frameworks to better capture the earliest research activities that feed into technology development. At the other end of the scale, some organizations have defined levels beyond TRL 9 to address post-deployment activities such as system improvement, optimization, or evolution. TRL 10 has been variously defined as “System improvement and optimization” or “Technology evolution and adaptation,” representing activities that enhance or extend an already operational technology. For instance, software systems that have achieved TRL 9 (proven in operational use) might undergo continuous improvement and updates that could be classified as TRL 10 activities. The Department of Energy has explored extensions beyond TRL 9 to better capture the ongoing evolution of energy technologies after initial deployment. Some organizations have developed modified TRL scales specifically for certain types of technologies. For software-intensive systems, where traditional hardware-focused TRL definitions may not adequately capture the development process, specialized Software Readiness Levels (SRL) have been created. These often include more detailed criteria for software testing, integration, and user

1.4 Methodologies for TRL Assessment

Building upon this foundation of TRL scale definitions and variations, we now turn our attention to the methodologies employed to conduct TRL assessments. The process of determining a technology’s readiness level is not merely an exercise in matching observations to predefined definitions; it is a sophisticated evaluation requiring careful consideration of evidence, application of structured methods, and often, the integration of diverse perspectives. The challenge lies in achieving an assessment that is both rigorous and defensible, providing stakeholders with confidence in the technology’s reported maturity while navigating the inherent complexities and uncertainties of technological development. Organizations have developed a rich tapestry of assessment approaches, ranging from highly quantitative, metrics-driven evaluations to those relying primarily on expert qualitative judgment, with many sophisticated hybrid frameworks blending the strengths of both paradigms. The choice of methodology depends heavily on factors such as the technology’s nature, the criticality of the assessment, the availability of objective data, the required level of confidence, and the specific needs of the stakeholders who will rely on the assessment results. Understanding these methodologies and their appropriate application is essential for conducting meaningful TRL assessments that truly inform decision-making rather than merely providing a superficial label.

Objective assessment methods form the bedrock of rigorous TRL evaluations, striving to minimize subjectivity by relying on measurable criteria and quantifiable evidence. These approaches are particularly valuable at higher TRL levels (4-9) where tangible components, prototypes, and systems exist, allowing for direct measurement of performance characteristics under defined conditions. At its core, objective assessment involves establishing clear, quantitative metrics that must be met or exceeded to demonstrate achievement of specific TRL criteria. For instance, a new battery technology seeking validation at TRL 5 might require objective demonstration of specific metrics such as energy density (e.g., >250 Wh/kg), cycle life (e.g., >1000 cycles

with <20% capacity degradation), charge/discharge rates (e.g., 3C continuous discharge), and performance under relevant environmental conditions (e.g., operation between -20°C and 60°C). The U.S. Department of Defense’s TRL Assessment Deskbook provides extensive guidance on objective metrics for various technology domains, emphasizing that “TRLs are determined by the demonstrated capabilities of the technology, not by the effort expended or the time remaining in a schedule.” Objective methods often employ structured tools like checklists, scorecards, and decision matrices that translate qualitative TRL definitions into specific, verifiable criteria. NASA’s Technology Readiness Assessment (TRA) process, detailed in its TRL Handbook, utilizes comprehensive checklists for each TRL level, requiring documented evidence against each criterion before a level can be certified. For example, achieving TRL 7 for a spacecraft instrument would necessitate objective evidence from operational environment testing, including specific performance data (e.g., signal-to-noise ratio, calibration accuracy, power consumption) measured under conditions simulating the intended mission environment, such as thermal vacuum testing or vibration testing. The James Webb Space Telescope’s mirror segments underwent exhaustive objective measurement at TRL 6, with each segment’s surface figure polished to within a few nanometers of the required prescription, verified through interferometric measurements under cryogenic conditions replicating space temperatures. Quantitative tools like Technology Readiness Calculators have been developed by organizations including the Air Force Research Laboratory and Sandia National Laboratories; these tools often incorporate weighted scoring systems where different evidence types and performance metrics contribute numerically to an overall TRL score, providing a more granular view of maturity within a level. The European Space Agency’s TRL assessment process similarly emphasizes objective evidence, requiring specific deliverables such as test reports, analysis documents, and inspection records for each TRL criterion. The strength of objective assessment lies in its transparency, reproducibility, and defensibility—when properly executed, two independent assessors applying the same objective criteria to the same evidence should arrive at the same TRL determination. This consistency is particularly crucial in high-stakes government procurement and funding decisions where billions of dollars and national security interests may hinge on the accuracy of TRL assessments. However, the limitations of purely objective methods become apparent at lower TRL levels (1-3) where technologies exist primarily as concepts or analytical models, making comprehensive quantitative measurement difficult or impossible, and in highly innovative domains where established metrics may not yet exist for novel technologies.

When objective measures prove insufficient or impractical, particularly for early-stage technologies or complex system-of-systems, subjective assessment through expert judgment becomes an indispensable component of TRL evaluation. Expert judgment leverages the accumulated knowledge, experience, and intuition of subject matter experts to interpret available evidence and make informed determinations about technology maturity. This approach recognizes that TRL assessment often involves evaluating complex, multifaceted phenomena where not all relevant factors can be easily quantified, and where contextual understanding plays a crucial role. The Delphi method, developed by the RAND Corporation in the 1950s, has been widely adapted for TRL assessments, particularly in contexts requiring consensus among diverse experts. In a Delphi-based TRL assessment, a panel of experts independently evaluates the technology against TRL criteria, providing their assessments and justifications. These assessments are then summarized and shared

anonymously with the panel, allowing experts to reconsider their views in light of others' perspectives without the influence of dominant personalities. This iterative process continues until consensus emerges or the range of opinions stabilizes. The U.S. Department of Energy has effectively employed Delphi-based approaches for evaluating emerging energy technologies like advanced nuclear reactor concepts or carbon capture systems, where objective data may be limited but expert insight is abundant. Another structured approach for subjective assessment is the Technology Readiness Assessment Workshop, where experts convene to discuss evidence, debate interpretations, and collectively determine TRL. The National Renewable Energy Laboratory (NREL) regularly conducts such workshops for renewable energy technologies, bringing together engineers, scientists, and industry representatives to evaluate TRL based on presented evidence and expert knowledge. However, subjective assessments are vulnerable to cognitive biases that can distort judgment. Optimism bias, where experts overestimate the maturity of technologies they are personally invested in, and anchoring bias, where initial assessments disproportionately influence final judgments, are common pitfalls. The infamous case of the Hubble Space Telescope's primary mirror flaw serves as a cautionary tale; subjective assessments during development failed to adequately question the null test setup used for mirror verification, leading to an incorrectly polished mirror that required a costly corrective mission. To mitigate such biases, best practices for expert judgment assessments include deliberately assembling diverse panels with varied perspectives and expertise, requiring explicit justification for assessments, using structured frameworks that force consideration of all relevant criteria, and employing independent reviewers to challenge assumptions. The European Space Agency's TRL assessment guidelines emphasize the importance of "independent verification" by experts not directly involved in the technology development, providing an additional check against overly optimistic internal assessments. When implemented rigorously, expert judgment can provide nuanced insights that purely objective methods might miss, particularly for revolutionary technologies where historical precedents and established metrics are lacking. The key is to structure the subjective process to maximize the value of expert insight while minimizing the influence of bias and unfounded opinion.

Recognizing the limitations of purely objective or subjective approaches, many organizations have developed sophisticated hybrid assessment frameworks that systematically integrate quantitative metrics with qualitative expert evaluation. These hybrid methodologies seek to leverage the strengths of both paradigms—the objectivity and transparency of metrics with the contextual understanding and flexibility of expert judgment—while mitigating their respective weaknesses. A prominent example is NASA's integrated Technology Readiness Level (iTRL) assessment process, developed for complex space systems. The iTRL framework combines a quantitative scoring system for specific technical attributes with qualitative evaluations by an independent review board. For each TRL criterion, assessors assign a score based on the quality and completeness of evidence (e.g., 0=no evidence, 1=limited evidence, 2=adequate evidence, 3=comprehensive evidence). These scores are aggregated to produce a quantitative TRL score, which is then reviewed by an expert panel that considers contextual factors not captured by the scoring system, such as technology novelty, integration complexity, and development risks. This dual approach was applied extensively during the development of the Mars Perseverance rover, where quantitative measurements of instrument performance were supplemented by expert judgment on the challenges of operating in the Martian environment. The Depart-

ment of Defense's Technology Readiness Assessment Calculator (TRAC) represents another sophisticated hybrid approach. TRAC employs a weighted scoring system where different types of evidence (e.g., test data, analysis, simulation results, expert opinion) and different performance attributes (e.g., functionality, reliability, manufacturability) contribute numerically to an overall TRL score. However, the calculator also includes "qualitative adjustment factors" that allow expert assessors to modify the score based on considerations like technology maturity uncertainty, system complexity, and development environment. This hybrid methodology was instrumental in assessing the TRL of the F-35 Lightning II's various subsystems, where objective performance data from flight tests was combined with expert evaluations of integration challenges and operational risks. Decision matrices form another common hybrid tool, particularly useful for evaluating system-of-systems where multiple technologies must be integrated. These matrices typically list TRL criteria as rows and assessment methods (both objective and subjective) as columns, with cells containing specific evaluation approaches and evidence requirements. The Federal Aviation Administration (FAA) has employed such matrices for assessing Next Generation Air Transportation System (NextGen) technologies, combining quantitative performance metrics from simulations and prototypes with qualitative safety assessments by aviation experts. A particularly effective hybrid framework is the Evidence-Based TRL Assessment (EBTRA) methodology developed by the Aerospace Corporation. EBTRA establishes a hierarchy of evidence types, with experimental data given higher weight than analysis or simulation, and simulation given higher weight than expert opinion. Assessors systematically catalog all available evidence against each TRL criterion, assign confidence levels to each piece of evidence, and then use a structured algorithm to determine the overall TRL, with provisions for expert override when the algorithm produces counterintuitive results. This approach proved valuable in assessing the TRL of space situational awareness technologies, where sensor performance data (objective) needed to be combined with expert evaluations of data fusion algorithms (subjective). The true power of hybrid approaches lies in their adaptability to different technological contexts and their ability to provide a more comprehensive and nuanced view of technology maturity than any single method could achieve. By consciously integrating quantitative and qualitative elements, these frameworks produce assessments that are both evidence-based and contextually aware, providing decision-makers with a robust foundation for technology investment and management decisions.

Regardless of the assessment methodology employed, the credibility and utility of any TRL determination ultimately depend on the quality and completeness of the documentation supporting it. Documentation and evidence requirements form the critical infrastructure that enables TRL assessments to be transparent, reproducible, and defensible. The types of evidence needed vary significantly across TRL levels, reflecting the progression from conceptual research to operational systems. At the earliest levels (TRL 1-3), evidence typically consists of scientific publications, theoretical analyses, conceptual designs, and proof-of-concept experimental data. For example, achieving TRL 3 for a novel materials science discovery would require documented experimental results demonstrating the material's key properties, such as peer-reviewed journal articles presenting data from laboratory-scale synthesis and characterization. As technologies advance to development stages (TRL 4-6), evidence requirements become more rigorous and specific. TRL 4 necessitates documentation of laboratory validation tests, including test plans, procedures, data reports, and analyses demonstrating component integration. The transition to TRL 5 requires evidence of testing in relevant

environments, such as environmental test reports documenting performance under conditions like thermal cycling, vibration, or vacuum. TRL 6 demands comprehensive documentation of system-level prototype demonstrations, including test reports, integration analyses, and risk assessments. For instance, validating a new automotive battery technology at TRL 6 would require detailed documentation of pack-level testing under simulated driving conditions, including performance data, thermal management results, and safety test outcomes. At the deployment stages (TRL 7-9), evidence requirements focus on operational validation and qualification. TRL 7 requires documentation of prototype demonstrations in operational environments, such as test reports from field trials or operational testing. TRL 8 necessitates comprehensive qualification documentation, including test reports, verification matrices, and certification evidence demonstrating that the actual system meets all requirements. TRL 9 requires evidence of successful operational performance, such as mission reports, operational data analyses, and user feedback documenting sustained operation in the intended environment. The International Space Station's life support systems, for instance, achieved TRL 9 only after extensive documentation of years of successful operational performance in the space environment. Standards and best practices for documenting TRL assessments have been established by leading organizations. NASA's TRL Handbook provides detailed guidance on evidence requirements for each level, emphasizing that "documentation must be sufficient to allow an independent assessor to reach the same conclusion about the TRL." The Department of Defense's Technology Readiness Assessment Deskbook similarly specifies documentation standards, including requirements for traceability between evidence and TRL criteria. ISO 16290:2013, the international standard for space system TRLs, includes comprehensive provisions for evidence documentation, requiring that "the basis for the TRL assessment shall be documented and traceable to the evidence." Maintaining assessment records for audit, review, and continuity is essential. Many organizations implement formal Technology Readiness Assessment Report (TRAR) templates that standardize documentation across projects. These reports typically include technology descriptions, evidence summaries, assessment methodologies, rationale for TRL determinations, identified risks, and recommendations. The European Space Agency requires such reports for all major technology developments, with records maintained for the entire project lifecycle. The role of these documentation practices extends beyond mere record-keeping; they enable knowledge transfer between project phases and teams, support independent reviews and audits, provide historical data for improving assessment methodologies, and create defensible records for acquisition and funding decisions. In high-stakes government programs, such as the Joint Direct Attack Munition (JDAM) program or the Commercial Crew Program, TRL documentation has been subject to rigorous scrutiny by Government Accountability Office (GAO) reviews and congressional oversight, underscoring its importance in accountability and transparency. Ultimately, robust documentation transforms TRL assessment from a subjective exercise into an evidence-based discipline, providing the foundation upon which sound technology management decisions are built and ensuring that the journey from concept to deployment is navigated with clarity and confidence.

As organizations continue to refine their TRL assessment methodologies, the interplay between objective metrics, expert judgment, hybrid frameworks, and rigorous documentation creates a multifaceted approach to evaluating technology maturity. These methodologies provide the essential tools for translating the theoretical structure of the TRL scale into practical, actionable assessments that guide critical decisions about

technology development, investment, and deployment. The art and science of TRL assessment lie not merely in applying these methods mechanically, but in selecting and adapting them appropriately to the specific technological context, available evidence, and stakeholder needs. This nuanced application of assessment methodologies enables organizations to navigate the complex landscape of technology maturation with greater precision and confidence, setting the stage for exploring how these approaches are tailored to the unique demands of different industries and technological domains.

1.5 Application in Different Industries

The methodologies and documentation practices that underpin rigorous TRL assessments, as explored in the previous section, find diverse expression across the technological landscape. While the fundamental principles of technology readiness assessment remain consistent, the implementation and adaptation of TRL frameworks vary significantly across different industries, each with its unique technological challenges, regulatory environments, and stakeholder expectations. This industry-specific tailoring of TRL assessment represents both the versatility of the framework and the ingenuity of practitioners in adapting it to contexts far removed from its aerospace origins. As we examine these diverse applications, we discover how the core TRL concept has been stretched, refined, and reimagined to serve sectors ranging from energy production to healthcare delivery, from software development to biotechnology innovation, each transformation revealing new dimensions of this powerful assessment tool.

The aerospace and defense industry stands as both the birthplace of TRL assessment and its most sophisticated practitioner, having refined the framework over decades of high-stakes technology development. In this sector, TRL assessment has evolved from a simple reporting tool to an integral component of the acquisition lifecycle, deeply embedded in program management, risk mitigation, and decision-making processes. The U.S. Department of Defense has institutionalized TRL assessment through numerous policy documents, including DoD Instruction 5000.02, “Operation of the Adaptive Acquisition Framework,” which mandates TRL evaluations at key program milestones. This formal integration ensures that technology maturity is explicitly considered before committing to major development phases, preventing the costly overruns that plagued earlier programs like the F-22 Raptor, where immature technologies contributed to a 40% cost increase over initial estimates. The Joint Strike Fighter (F-35) program learned from these experiences, implementing rigorous TRL gates that required critical technologies such as the helmet-mounted display system and electro-optical targeting system to reach TRL 6 before the program’s Milestone B decision, though subsequent challenges revealed the limitations of TRL assessment when applied to highly integrated systems. The aerospace industry has developed particularly sophisticated approaches to assessing system-of-systems, where multiple technologies at different readiness levels must be integrated. NASA’s exploration programs, for example, employ a “TRL matrix” approach that evaluates not just individual component technologies but also their integration readiness, recognizing that a system is only as mature as its least mature critical component. This nuanced approach was evident in the James Webb Space Telescope program, where individual technologies like the segmented mirror system achieved TRL 6-7 before final integration, but the overall system required additional testing to reach TRL 8. The European Space Agency has similarly re-

fined its TRL assessment approach for complex missions, developing the “TRL+” concept that incorporates additional factors like software maturity and ground segment readiness. In defense applications, TRL assessment has been extended to address the unique challenges of military systems, including cyber resilience and electronic warfare capabilities. The Army’s Rapid Capabilities Office, for instance, has adapted TRL frameworks for rapid prototyping of electronic warfare systems, creating accelerated assessment pathways that maintain rigor while supporting faster fielding cycles. The defense industry has also pioneered the integration of TRL with other readiness assessments, particularly Manufacturing Readiness Levels (MRL) and Integration Readiness Levels (IRL), to create a comprehensive view of technology viability. Lockheed Martin’s application of this integrated approach to the F-35 production system helped identify manufacturing risks early, allowing for proactive mitigation before they became program-level issues. The sophistication of TRL assessment in aerospace and defense reflects both the high stakes of the technologies involved and the decades of experience practitioners have accumulated with the framework, resulting in assessment methodologies that have become industry benchmarks for rigor and comprehensiveness.

The energy sector has embraced TRL assessment with particular enthusiasm, adapting the framework to address the unique challenges of energy technology development, including long development timelines, massive scale-up requirements, and complex integration with existing infrastructure. The U.S. Department of Energy has been at the forefront of this adaptation, developing comprehensive TRL guidance tailored to energy technologies that addresses the specific challenges of moving from laboratory-scale demonstrations to utility-scale deployments. Unlike aerospace systems, which often transition directly from prototype to operational use, energy technologies typically face a daunting “valley of death” between pilot-scale demonstrations (TRL 6-7) and commercial deployment (TRL 9), with scale-up factors of 100 to 1000 times common. The DOE’s Geothermal Technologies Office, for instance, has developed detailed TRL definitions for enhanced geothermal systems that specifically address the challenges of demonstrating reservoir performance at progressively larger scales, from laboratory experiments (TRL 3-4) through single-well demonstrations (TRL 5-6) to multi-well commercial systems (TRL 8-9). This tailored approach has enabled more

1.6 TRL Assessment in Government and Defense

The energy sector’s adaptation of TRL assessment to address the unique challenges of scaling technologies from laboratory demonstrations to commercial deployment demonstrates the framework’s remarkable versatility. However, it is within government and defense contexts that TRL assessment has been most extensively developed, refined, and institutionalized, evolving from a simple reporting tool to a cornerstone of technology management and acquisition processes. The journey of TRL within these contexts reflects the critical importance of technology readiness assessment in high-stakes environments where national security, public safety, and vast financial resources are at stake. Government and defense organizations have not only embraced TRL assessment but have transformed it into sophisticated systems that govern how technologies are developed, acquired, and deployed, setting standards that many other industries now follow.

The U.S. Department of Defense has played a pivotal role in the evolution and institutionalization of TRL assessment, transforming it from a NASA-developed concept into a fundamental element of defense acquisition

policy. The DoD's formal adoption of TRL began in the mid-1990s, driven by the need to address persistent problems in defense acquisition programs, including cost overruns, schedule delays, and performance shortfalls often stemming from the premature integration of immature technologies. The turning point came with the 1995 publication of the "DoD Technology Readiness Assessment Deskbook," which provided comprehensive guidance on TRL definitions, assessment methodologies, and implementation practices specifically tailored to defense systems. This document marked the beginning of TRL's formal integration into the defense acquisition process, establishing a common language for technology evaluation across the department's diverse components. By 1999, TRL assessment had become sufficiently institutionalized to be incorporated into the Defense Acquisition Guidebook, and by 2003, it was formally mandated in DoD Instruction 5000.02, "Operation of the Adaptive Acquisition Framework," which requires TRL evaluations at key program milestones. This formal integration ensures that technology maturity is explicitly considered before committing to major development phases, creating a structured approach to technology risk management that has become a hallmark of modern defense acquisition. The implementation of TRL assessment within the DoD has been characterized by continuous refinement and adaptation to address emerging challenges. Early applications focused primarily on hardware technologies, but as software-intensive systems became increasingly prevalent, the department developed specialized guidance for software TRL assessment, recognizing that traditional hardware-focused definitions were inadequate for evaluating software maturity. The DoD's Software Engineering Institute contributed significantly to this effort, developing complementary frameworks like the Software Capability Maturity Model that could be integrated with TRL assessments for software-intensive systems. The Air Force, Navy, and Army have each developed service-specific implementations of TRL assessment tailored to their unique technology portfolios and acquisition processes. The Air Force Research Laboratory, for instance, has pioneered the use of TRL assessments for managing its science and technology portfolio, employing sophisticated risk-adjusted TRL metrics that account for both readiness level and the uncertainty associated with the assessment. The Naval Sea Systems Command has developed detailed TRL guidance for shipboard systems, addressing the unique challenges of maritime environments and platform integration. The Army's Program Executive Office for Aviation has implemented rigorous TRL gates for rotorcraft systems, requiring critical technologies to achieve specific maturity levels before proceeding to development and production. These service-specific adaptations demonstrate the flexibility of the TRL framework while maintaining consistency with department-wide standards. The impact of TRL assessment on defense acquisition programs has been profound. The Joint Direct Attack Munition (JDAM) program represents a success story where rigorous TRL assessment contributed to on-time, on-budget delivery of a critical capability. The program required that key technologies, particularly the GPS guidance system, achieve TRL 6 before entering the engineering and manufacturing development phase, ensuring that technical risks were adequately mitigated before major production commitments. Conversely, the F-35 Lightning II program illustrates the challenges of TRL assessment when applied to highly integrated systems. While the program implemented TRL gates for individual technologies, the complexity of integrating these technologies into a cohesive system revealed limitations in traditional TRL approaches, leading to cost increases and schedule delays. This experience prompted the DoD to refine its TRL assessment methodologies, placing greater emphasis on integration readiness and system-level testing. The DoD's continued evolution of TRL assessment is evident in recent initiatives like the Adaptive Acquisition Framework, which tailors acquisition

pathways to different types of capabilities while maintaining TRL assessment as a common element across all pathways. The department has also expanded its use of TRL assessment to include emerging technology domains like artificial intelligence, cyber systems, and hypersonic weapons, developing specialized criteria and assessment methodologies for these cutting-edge areas. Through this continuous refinement and institutional integration, the DoD has transformed TRL assessment from a simple reporting tool into a sophisticated system that underpins how the nation develops and acquires critical defense capabilities.

The international diffusion of TRL assessment to defense and space agencies beyond the United States represents a fascinating case study in the globalization of technology management practices. As other nations recognized the value of structured technology readiness assessment, they adapted the TRL framework to their specific contexts, creating a rich tapestry of international implementations that share core principles while reflecting unique national priorities and organizational structures. The European Space Agency (ESA) emerged as one of the earliest international adopters, beginning its experimentation with TRL concepts in the mid-1990s before formally adopting a nine-level scale based on NASA's framework in 1998. However, the European implementation was not merely a transatlantic import; ESA carefully adapted the definitions to reflect its specific organizational structure and technology development processes, placing greater emphasis on technology verification and validation procedures consistent with European engineering standards. This adaptation process illustrates how TRL frameworks maintain their core principles while flexing to accommodate different institutional contexts. ESA's TRL implementation became sufficiently sophisticated that by 2008, it was incorporated into the European Cooperation for Space Standardization (ECSS) engineering standards, specifically in ECSS-E-ST-10-02C "Space engineering – Technology readiness levels." This standardization effort represented a significant milestone in TRL's evolution, moving the framework beyond individual agency practices to formalized international standards. The success of ESA's implementation spurred adoption by other European space agencies and organizations, including the French Centre National d'Études Spatiales (CNES), the German Aerospace Center (DLR), and the UK Space Agency. Each of these agencies developed their own specific implementations while maintaining consistency with the broader European framework, creating a harmonized approach to technology readiness assessment across European space activities. In the defense domain, NATO has played a particularly important role in standardizing TRL assessment across alliance members. Recognizing that collaborative defense programs required a common understanding of technology maturity, NATO developed its own TRL framework to facilitate technology cooperation among member nations. The NATO Research and Technology Organisation (RTO), now known as the NATO Science & Technology Organization (STO), published its first TRL guidance in the early 2000s, creating a framework that balanced consistency with national implementations. This NATO framework has proven invaluable for multinational programs like the Eurofighter Typhoon, where partner nations needed a common language for evaluating technology readiness across different national assessment systems. The Typhoon program, which involved the UK, Germany, Italy, and Spain, benefited from this harmonized approach, enabling more effective management of technology risks across the multinational partnership. Beyond Europe, other nations have developed their own TRL implementations, often drawing from both NASA and ESA models while tailoring them to national priorities and capabilities. The Japan Aerospace Exploration Agency (JAXA) has implemented a sophisticated TRL framework that places partic-

ular emphasis on reliability and quality assurance, reflecting Japan’s engineering culture and the high stakes of its space program. The Indian Space Research Organisation (ISRO) has adapted TRL assessment to its unique context of developing advanced space capabilities with limited resources, creating a framework that emphasizes cost-effective technology maturation pathways. The Canadian Space Agency (CSA) has developed TRL guidance specifically tailored to Canada’s niche capabilities in space robotics and satellite communications, supporting successful programs like the Canadarm robotic systems used on the Space Shuttle and International Space Station. The international standardization of TRL assessment reached a significant milestone in 2013 with the publication of ISO 16290:2013 “Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria assessment.” This international standard, developed collaboratively by experts from NASA, ESA, and other national space agencies, represented the first truly global consensus on TRL definitions and assessment criteria, cementing the framework’s status as an international best practice. The development of this ISO standard was a complex undertaking, requiring harmonization of different national approaches while preserving the flexibility needed for diverse applications. The resulting standard provides detailed definitions for each TRL level along with comprehensive guidance on assessment methodologies, creating a foundation for global consistency in technology readiness evaluation. The international journey of TRL assessment demonstrates how a practical management tool developed to address specific challenges within one organization can evolve into a global standard through recognition of its universal value and adaptation to diverse contexts. This global diffusion has not been without challenges, as different nations and organizations have sometimes struggled with varying interpretations of TRL criteria or different approaches to evidence requirements. However, these challenges have generally been addressed through continued dialogue and refinement of standards, leading to increasingly harmonized practices. The result is a global ecosystem of TRL assessment that shares core principles while accommodating national and organizational differences, facilitating international cooperation in technology development while respecting diverse approaches to innovation and acquisition.

The integration of TRL assessment into government procurement and funding decisions represents one of the most significant applications of the framework, transforming how public agencies evaluate, select, and manage technology investments. Across government agencies, TRL assessments have become essential tools for informing procurement decisions, structuring solicitations, evaluating proposals, and managing contract performance, creating a more systematic and evidence-based approach to public technology acquisition. The U.S. Department of Defense provides the most extensive example of TRL integration in procurement processes, where technology readiness assessments directly influence contract requirements, source selection criteria, and program milestone decisions. DoD procurement regulations now explicitly reference TRL requirements, with solicitations often specifying minimum TRL levels for proposed technologies and requiring offerors to substantiate their TRL claims with detailed evidence. This practice was formalized in the 2003 Defense Acquisition Guidebook, which established TRL as a key consideration in source selection and provided guidance on incorporating TRL requirements into solicitations. The impact of this integration is evident in programs like the Navy’s Virginia-class submarine, where procurement specifications explicitly defined TRL requirements for critical technologies such as the acoustic quieting systems and sonar arrays. These requirements ensured that contractors could not bid on the program without demonstrating that their

proposed technologies had achieved sufficient maturity, significantly reducing technical risk during subsequent development. The Army's Comanche helicopter program, which was cancelled in 2004 after billions of dollars in expenditures, provided a cautionary tale that reinforced the importance of TRL requirements in procurement. Investigations following the program's termination revealed that several critical technologies had not achieved the necessary maturity before the program entered full-scale development, contributing to technical challenges and cost overruns. This experience led to more rigorous enforcement of TRL requirements in subsequent defense procurements, with programs like the Joint Strike Fighter implementing stricter TRL gates based on the lessons learned. Beyond the DoD, other U.S. government agencies have similarly integrated TRL assessment into their procurement processes. The Department of Energy uses TRL assessments extensively in its procurement of energy technologies, particularly through programs like the Advanced Research Projects Agency-Energy (ARPA-E), which requires technologies to achieve specific readiness levels before qualifying for certain types of funding or procurement support. The National Aeronautics and Space Administration (NASA) incorporates TRL requirements into its procurement of spacecraft and instrument systems, with solicitations for missions like the Mars Perseverance rover specifying TRL requirements for key technologies to ensure they could be successfully integrated and operated in the harsh Martian environment. The Department of Homeland Security has adopted TRL assessment for procuring security technologies, using readiness levels to evaluate proposals for border surveillance systems, cybersecurity tools, and other critical capabilities. The Federal Aviation Administration (FAA) employs TRL assessments in its procurement of air traffic control systems, recognizing that the complex integration requirements of these systems demand careful management of technology maturity. The General Services Administration (GSA) has begun incorporating TRL considerations into its procurement of information technology systems, using readiness levels to evaluate proposals for cloud computing services, artificial intelligence applications, and other emerging digital capabilities. The integration of TRL assessment into government procurement extends beyond initial contract awards to ongoing contract management and performance evaluation. Many agencies now use TRL assessments as a basis for structuring incremental funding releases, with payments tied to the achievement of specific technology readiness milestones. This approach, often referred to as "TRL-based earned value management," creates a more objective basis for measuring contractor performance and managing financial risk. The Defense Advanced Research Projects Agency (DARPA) has been particularly innovative in this area, developing sophisticated contracting mechanisms that align funding with demonstrated technology maturation. DARPA's Adaptive Vehicle Make program, which aimed to revolutionize military vehicle development, employed a contracting approach that provided incremental funding as technologies progressed through predefined TRL milestones, creating strong incentives for contractors to demonstrate tangible progress rather than merely expending effort. Government agencies are also increasingly using TRL assessments to structure public-private partnerships and other innovative acquisition arrangements. The Department of Energy's Loan Programs Office, for instance, uses TRL assessments to evaluate the technical viability of projects seeking loan guarantees, with readiness levels playing a key role in determining loan terms and conditions. Similarly, NASA's use of public-private partnerships for commercial cargo and crew services to the International Space Station incorporates TRL assessments to ensure that proposed systems have achieved sufficient maturity before receiving government support. The integration of TRL assessment into government procurement has not been without challenges. Agencies have some-

times struggled with inconsistent application of TRL criteria, overly optimistic assessments by contractors, or difficulties in evaluating novel technologies that don't fit neatly into traditional TRL categories. These challenges have led to the development of more sophisticated assessment methodologies, greater emphasis on independent verification, and increased training for procurement professionals in technology evaluation. Despite these challenges, the trend toward greater integration of TRL assessment into government procurement continues to grow, driven by the demonstrated benefits of more systematic, evidence-based technology acquisition. This evolution represents a fundamental shift in how government agencies approach technology procurement, moving from processes focused primarily on cost and schedule to those that explicitly consider technology maturity as a critical factor in acquisition success.

The development of government standards and implementation guidance for TRL assessment represents the culmination of decades of experience in applying the framework across diverse contexts and programs. These standards and guidance documents provide the foundation for consistent, defensible TRL assessments, establishing common definitions, methodologies, and best practices that enable organizations to evaluate technology readiness in a systematic manner. The evolution of these documents reflects the maturation of TRL assessment from an informal practice to a formal discipline, with each iteration incorporating lessons learned from previous applications and addressing emerging challenges in technology management. The U.S. Department of Defense has been at the forefront of this standardization effort, producing a series of increasingly sophisticated guidance documents that have shaped TRL assessment practices across government and industry. The DoD's journey began with the 1995 "Technology Readiness Assessment Deskbook," which provided basic definitions and assessment guidance. This was followed by the 1999 "DoD Technology Readiness Assessment Deskbook" (updated in 2001 and again in 2003), which expanded the guidance to address software technologies and system-of-systems integration. The 2005 "Technology Readiness Assessment (TRA) Deskbook" represented another significant step forward, providing more detailed assessment criteria and emphasizing the importance of evidence-based evaluations. The current DoD guidance, embodied in the 2011 "Technology Readiness Assessment (TRA) Guidance" and the 2019 "DoD Technology Readiness Assessment Deskbook," reflects decades of cumulative experience and refinement. These documents establish a comprehensive framework for TRL assessment, including detailed definitions for each readiness level, guidance on evidence requirements, procedures for independent verification, and methodologies for addressing special cases like software-intensive systems and system-of-systems. The DoD has also developed specialized guidance for specific technology domains, including the 2012 "Assessing the Readiness of Technology in NASA Programs" handbook (developed in collaboration with NASA) and the 2017 "Cyber TRL" guidance for evaluating the maturity of cybersecurity technologies. These documents are not merely prescriptive standards; they represent the accumulated wisdom of countless technology development programs, capturing both successful practices and cautionary tales that can inform future assessments. NASA has similarly developed comprehensive guidance for TRL assessment, beginning with the 1995 white paper that first formalized the concept and evolving through successive iterations to the current 2015 "NASA Technology Readiness Level (TRL) Handbook." This handbook provides detailed guidance on TRL definitions, assessment methodologies, evidence requirements, and reporting practices, tailored specifically to NASA's space technology development context. NASA's guidance is particularly notable for its empha-

sis on independent verification and validation of TRL assessments, reflecting the agency's experience with high-stakes space missions where technology failures can have catastrophic consequences. The NASA handbook also provides extensive examples and case studies illustrating how TRL assessment has been applied to specific technologies and programs, creating a rich repository of practical knowledge that can inform future assessments. Beyond the DoD and NASA, other U.S. government agencies have developed their own TRL guidance documents, often adapting the frameworks established by the defense and space communities to their specific contexts. The Department of Energy's 2009 "Technology Readiness Assessment Guide" addresses the unique challenges of energy technology development, particularly the scale-up requirements that distinguish energy technologies from many aerospace and defense systems. The Department of Homeland Security's 2017 "Technology Readiness Assessment Guidebook" focuses on security technologies, with specialized criteria for evaluating systems like border surveillance sensors, cybersecurity tools, and explosive detection systems. The Federal Aviation Administration's 2018 "TRL Guidance for NextGen Technologies" addresses the complex integration requirements of air traffic control modernization, emphasizing interoperability and safety considerations. Internationally, standardization efforts have produced several influential guidance documents. The European Space Agency's 2011 "Technology Readiness Levels Handbook for Space Applications" provides comprehensive guidance tailored to European space programs,

1.7 TRL Assessment in Commercial Innovation

While government and defense organizations have transformed TRL assessment into a cornerstone of public technology management, the commercial innovation ecosystem has embraced these methodologies with equal enthusiasm, adapting them to the unique dynamics of venture capital, corporate research and development, and technology commercialization. The migration of TRL assessment from public sector institutions to private enterprise represents a fascinating evolution of the framework, reflecting its fundamental value in managing technology risk across vastly different contexts. In the fast-paced, high-stakes world of commercial innovation, where capital efficiency and speed to market are paramount, TRL assessment has emerged as an essential tool for investors, entrepreneurs, and corporate innovators seeking to navigate the complex journey from scientific discovery to commercial success.

In the venture capital ecosystem, TRL assessment has revolutionized how investors evaluate technology opportunities, providing a structured framework for quantifying technical risk and informing investment decisions. Venture capitalists, whose business model depends on identifying promising technologies at the right stage of development, have found TRL assessment particularly valuable for creating a common language between scientists, engineers, and financial professionals. Kleiner Perkins, one of Silicon Valley's most venerable venture firms, began systematically incorporating TRL assessments into their due diligence process in the early 2000s, recognizing that traditional financial metrics alone were insufficient for evaluating deep technology investments. The firm developed a proprietary adaptation of the TRL framework that bridges the gap between technical readiness and commercial viability, helping partners evaluate technologies ranging from early-stage biotech breakthroughs to more mature software platforms. This approach proved instrumental in their investment in Genentech, where TRL assessments helped validate the readiness

of monoclonal antibody technologies before committing significant capital. Andreessen Horowitz (a16z) has similarly embraced TRL assessment, particularly for their bio fund and deep tech investments, using readiness levels to structure investment theses and develop milestones for portfolio companies. The firm's evaluation of Moderna's mRNA technology platform prior to its IPO relied heavily on TRL assessments that demonstrated the technology's progression from laboratory experiments (TRL 3-4) to clinical validation (TRL 6-7), providing confidence in the scientific foundation despite the company's lack of commercial products at the time. Sequoia Capital has developed what they call "Commercial TRL" frameworks that extend traditional technical readiness assessments to include market readiness factors, creating a more comprehensive view of investment opportunities. This integrated approach was particularly valuable in their evaluation of cloud computing companies like Snowflake, where technical readiness needed to be evaluated alongside market adoption and competitive positioning. The application of TRL assessment in venture capital extends beyond initial investment decisions to ongoing portfolio management. Many firms now require their portfolio companies to report progress against TRL milestones as a condition of follow-on funding, creating objective metrics for measuring technical progress that complement traditional business metrics. Benchmark Capital, for instance, implemented a TRL-based reporting system for their enterprise software investments, helping them identify which companies were making genuine technical progress versus those that were primarily optimizing business models without advancing core technology. This approach enabled more informed decisions about additional funding rounds and strategic pivots. The influence of TRL assessment on valuation models represents another significant development in venture capital. Traditionally, startup valuation has relied heavily on financial projections, market size, and team quality, with technical risk often assessed qualitatively. However, firms like Lux Capital have begun incorporating TRL-based discount rates into their valuation models, assigning higher discounts to technologies at lower readiness levels to account for the increased technical risk. This quantitative approach was particularly evident in their investment in quantum computing companies, where the significant technical uncertainties associated with this emerging technology demanded a more structured approach to risk assessment. The adaptation of TRL frameworks for venture capital has not been without challenges. The traditional TRL scale, developed for government programs with multi-year development cycles, sometimes struggles to accommodate the rapid iteration cycles characteristic of software startups and other digital technologies. To address this limitation, firms like Union Square Ventures have developed "Agile TRL" frameworks that better align with continuous development methodologies, using shorter assessment cycles and more granular readiness levels for rapidly evolving technologies. Another challenge has been the tendency of entrepreneurs to overstate technology readiness, a phenomenon sometimes called "TRL inflation" in venture circles. In response, firms like Greylock Partners have implemented independent technical verification processes, engaging third-party experts to validate TRL claims before making investment decisions. This practice proved valuable during the investment boom in clean energy technologies, where independent verification helped distinguish genuinely innovative approaches from concepts that were technically immature despite impressive presentations. The integration of TRL assessment into venture capital has also influenced deal structuring, with firms increasingly using TRL-based milestones to trigger funding releases and adjust valuation. Khosla Ventures, known for its investments in breakthrough technologies, has pioneered the use of TRL-based tranching financing, where capital is released as technologies achieve specific readiness milestones. This approach was applied

effectively to their investment in biofuels companies, where funding was tied to demonstrations of progressively larger-scale production capabilities at specific TRL levels. Despite these adaptations, venture capital firms continue to refine their approaches to TRL assessment, recognizing that while the framework provides invaluable structure, it must be flexibly applied to accommodate the diverse technologies and business models in their portfolios. The evolution of TRL assessment in venture capital represents a significant convergence of technical and financial evaluation methodologies, creating more sophisticated approaches to technology investment that better balance technical potential with market realities.