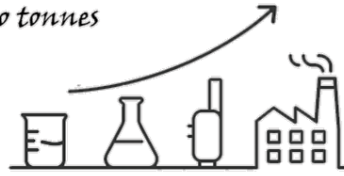




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From Lab to Market: Navigating the Scale-Up Gauntlet in Critical Minerals Processing with TRL and MRL Frameworks

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From Lab to Market: Navigating the Scale-Up Gauntlet in Critical Minerals Processing with TRL and MRL Frameworks

Alternate Title: Navigating the Gauntlet: TRL/MRL Methodologies and the Path to Commercialization in Critical Minerals

PREPARED BY:

Dr Palash Gangopadhyay, PhD
Delta 3 Core Tech LLC

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Table of Contents

Cover Page	Error! Bookmark not defined.
Author, & Licensing Information	Error! Bookmark not defined.
SUMMARY	3
Executive Summary	3
1. Recent Evolution in TRL & MRL Methodologies	3
2. Application in the Critical Minerals Industry	3
3. The "Valley of Death" and the McNulty Curve	4
4. How delta3coretec Navigates the Path Forward	4
By embedding the disciplined methodologies of TRL and MRL into a company's DNA, we turn the perilous journey of innovation into a manageable, milestone-driven process.	5
From Lab to Market: Navigating the Scale-Up Gauntlet in Critical Minerals Processing with TRL and MRL Frameworks	5
Executive Summary	5
The Dual Frameworks of Readiness: An In-Depth Analysis of TRL and MRL Methodologies	6
Technology Readiness Levels (TRLs): Assessing "Can it Work?"	6
Manufacturing Readiness Levels (MRLs): Assessing "Can We Build It?"	8
The TRL-MRL Interdependency: A Symbiotic and Perilous Relationship	10
Application in the Critical Minerals Sector: A High-Stakes Environment	11
The Strategic Imperative and Inherent Risks of the Midstream	11
TRL/MRL as an Investment and De-Risking Tool for Critical Minerals	12
Navigating the Gauntlet of Scale-Up: The Valley of Death and the McNulty Curve	13
The Valley of Death (TRL 4-7 / MRL 4-7): The Chasm Between Lab and Pilot	13
The Production Ramp-Up (MRL 7-10) and the McNulty Curve	14
Integrating the Frameworks: A Predictive Model for Success	16
Strategic Partnership for Commercialization: The Role of delta3coretec	16
De-Risking the Roadmap (TRL 1-4 / MRL 1-4): Techno-Economic Analysis	17
Bridging the Valley of Death (TRL 4-7 / MRL 4-7): Process Scale-Up	17
Ensuring a "Series 1" Ramp-Up (TRL 8-9 / MRL 8-10): QA/QC and Supply Chain	18
Conclusion and Strategic Recommendations	18
Appendix: TRL/MRL Self-Assessment Cheat Sheet for Critical Minerals Processing	20
References	Error! Bookmark not defined.



SUMMARY

Palash Gangopadhyay, PhD
Delta 3 Core Tech LLC

Executive Summary

The journey from a laboratory concept to a commercially viable product is fraught with challenges, particularly in capital-intensive sectors like critical minerals processing. The U.S. Department of Defense (DoD), and by extension other federal agencies like the Department of Energy (DOE), have refined Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) frameworks to de-risk this process. Recent updates emphasize a more integrated and disciplined approach to technology maturation. For startups and incumbents in the critical minerals space, mastering these methodologies is no longer optional—it is the critical path to securing funding, managing scale-up, and successfully bridging the notorious "valley of death." This report analyzes the current TRL/MRL landscape, its direct application to the critical minerals industry, and how strategic partners like delta3coretec can facilitate this complex journey.

1. Recent Evolution in TRL & MRL Methodologies

Based on the latest 2025 guidebooks, the core principles of TRL and MRL have been clarified to foster a more holistic view of technology maturation. Key changes and points of emphasis include:

- **Integrated Assessment:** There is a stronger push to assess TRLs and MRLs concurrently. Previously, manufacturing readiness was often an afterthought, leading to technologies that were mature in theory (high TRL) but impossible to produce at scale (low MRL). The updated frameworks treat them as two threads of the same rope, ensuring that as technology matures, the capability to manufacture it matures in lockstep.
- **Emphasis on Independence and Rigor:** The 2025 TRA Guidebook, reflecting changes from the FY25 NDAA, has removed references to waivers and certifications. This signals a move towards more stringent and independent assessments, making it harder to "game the system." A technology's readiness level must be demonstrated with empirical data, not just declared.
- **Standardized Language:** The MRL Deskbook for 2025 focuses on creating common language around "manufacturing vs. production" and "readiness vs. maturity." This standardization is crucial for clear communication between technical teams, management, investors, and government agencies.

2. Application in the Critical Minerals Industry

The critical minerals sector—encompassing the extraction, processing, and recycling of elements like lithium, cobalt, and rare earths—is a focal point for national security and economic strategy. However, new technologies in this field face immense scale-up hurdles. This is where the TRL/MRL framework becomes indispensable.

- **For Startups:** A startup with a novel solvent extraction technique for lithium must prove its



technology works. The TRL scale provides a clear roadmap:

- **TRL 1-3:** Basic research, proving the chemical principles in a beaker.
- **TRL 4-6:** Building a bench-scale or small pilot module to process kilograms of material, demonstrating the process in a relevant environment. This is the first major scale-up hurdle.
- **For Incumbents:** An established mining company looking to adopt a new, more environmentally friendly leaching process would use the MRL scale to manage risk:
 - **MRL 1-4:** Identifying and characterizing necessary materials, proving manufacturing feasibility at the lab scale.
 - **MRL 5-7:** Developing a pilot production line, qualifying suppliers for critical equipment and reagents, and proving the process can meet quality targets repeatably.

For both, the frameworks provide a universal language to communicate progress to investors and federal bodies like the DOE, which offers substantial funding through programs that often mandate TRL progression as a condition for continued support.

3. The "Valley of Death" and the McNulty Curve

Two concepts define the financial and operational challenges of scale-up, which the TRL/MRL framework helps to navigate.

The Valley of Death: This is the notorious funding gap that occurs around **TRL 4-6**. At this stage, initial government research grants have often been exhausted, but the technology is still too risky and unproven to attract significant private investment. It is the transition from a successful lab experiment to a functioning prototype or pilot system. Crossing this valley requires demonstrating not just that the technology works, but that it is on a clear path to being manufacturable and economical. A rigorous TRL/MRL assessment provides the credible, third-party validation needed to build investor confidence.

The McNulty Curve (The "S-Curve" of Cost): This concept illustrates that the cost of maturation is not linear. The costs associated with moving from TRL 1 to 4 are relatively small. However, the cost to build a pilot plant (TRL 5-6) and then a full-scale demonstration facility (TRL 7-8) increases exponentially. The TRL/MRL framework forces organizations to anticipate these costs by addressing manufacturing and supply chain issues early, preventing projects from failing due to unforeseen capital requirements during the steepest part of the curve.

4. How delta3coretec Navigates the Path Forward

Successfully navigating the TRL/MRL gauntlet requires specialized expertise that often lies outside the core competencies of a founding technical team. delta3coretec provides the strategic and operational support necessary to bridge these gaps and ensure a smooth transition from concept to commercialization.

- **Roadmap & Milestone Planning:** We work with clients to develop a fully integrated product and technology roadmap where TRL and MRL milestones are clearly defined, scheduled, and budgeted. This prevents the common pitfall of advancing one area (e.g., technology) without



considering the other (e.g., manufacturing).

- **Gap Analysis and Readiness Assessments:** Our experts conduct rigorous, independent TRL and MRL assessments, identifying critical gaps in technology, manufacturing, supply chain, and quality systems. This provides an honest baseline and a clear action plan for reaching the next level.
- **Bridging the Valley of Death:** We help prepare the data-driven business cases and technical validation packages that investors and government agencies require. By translating technical progress into the standardized language of TRL and MRL, we de-risk the investment and increase the probability of securing crucial scale-up funding.
- **Scale-Up Project Management:** delta3coretec provides hands-on management through the most challenging scale-up phases (TRL 4-7), helping clients design, build, and commission pilot and demonstration facilities while managing the exponential cost increases defined by the McNulty Curve.

By embedding the disciplined methodologies of TRL and MRL into a company's DNA, we turn the perilous journey of innovation into a manageable, milestone-driven process.

From Lab to Market: Navigating the Scale-Up Gauntlet in Critical Minerals Processing with TRL and MRL Frameworks

Executive Summary

The United States faces a strategic imperative to build a domestic critical minerals processing industry, thereby mitigating profound national security and economic vulnerabilities tied to foreign supply chains. However, startups and innovators in this sector face a perilous path from lab-scale discovery to profitable, full-scale production. This journey, often traversing a chasm known as the "valley of death," is fraught with technical, manufacturing, and financial risks that are frequently underestimated by stakeholders. The high capital intensity and long lead times inherent in minerals processing amplify these risks, leading to a high rate of project failure and deterring investment.

A disciplined, integrated application of the Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) frameworks provides the essential de-risking methodology to navigate this gauntlet. Originating from NASA and the Department of Defense (DoD), these frameworks are not academic exercises but vital, structured tools for strategic planning, attracting investment, and ensuring a successful production ramp-up. They provide a common, objective language for assessing maturity and managing risk across technical and manufacturing domains.

This report demonstrates that early-stage, rigorous TRL and MRL assessments serve as a leading indicator of a project's ultimate commercial success, a success often quantified by the mining



industry's empirical benchmark, the McNulty curve. A project's performance during its production ramp-up is not a matter of chance; it is predetermined by the thoroughness of its development and de-risking activities in the preceding phases. The analysis will show a direct causal link between successfully navigating the TRL 4-7 "valley of death" and achieving a best-in-class "Series 1" production ramp-up. Furthermore, this report details how specialized expertise, such as that offered by consultancies like delta3coretec, is critical for translating these frameworks into practice. Such expertise is indispensable for navigating the complex scale-up process, transforming high-potential technology into a bankable, commercial-scale operation capable of securing a resilient domestic supply chain.

The Dual Frameworks of Readiness: An In-Depth Analysis of TRL and MRL Methodologies

Successfully commercializing a new technology, particularly in a capital-intensive sector like critical minerals processing, requires a dual understanding of maturity: the maturity of the technology itself and the maturity of the processes required to manufacture it at scale. The U.S. government, primarily through the Department of Defense (DoD) and Department of Energy (DOE), has formalized the assessment of these two dimensions through two distinct but deeply interconnected frameworks: Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs). These are not merely checklists but comprehensive assessment methodologies that provide a common vocabulary for risk management, decision-making, and strategic planning.¹

Technology Readiness Levels (TRLs): Assessing "Can it Work?"

The TRL scale is a systematic metric used to assess the maturity of a particular technology from basic research to operational deployment.³ Its primary purpose is to provide a consistent, uniform language for discussing technical maturity, managing risk, and informing decisions about technology development and transition.³ A formal Technology Readiness Assessment (TRA) is the process by which a TRL is determined.⁵

Foundational Principles and the 2025 DoD Framework

Originally developed by NASA in the 1970s, the TRL framework has been adopted and refined by the DoD, with the most current guidance articulated in the February 2025 *Technology Readiness Assessment Guidebook*.⁵ The framework consists of a nine-level scale that tracks a technology's evolution. A key aspect of this progression is the environment in which the technology is tested. A technology advances from a controlled **laboratory environment** (TRL 4), to a simulated **relevant environment** that mimics the most stressing aspects of operational use (TRL 5-6), and finally to a true **operational environment** (TRL 7 and beyond).⁵

The DoD defines distinct criteria for both hardware and software, recognizing their different development pathways.



Table 1: DoD Hardware TRL Definitions (2025)

TRL	Definition	Description
1	Basic principles observed and reported.	Scientific research begins to be translated into applied R&D.
2	Technology concept and/or application formulated.	Invention begins; practical applications are speculative and supported by analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated, including lab studies to physically validate analytical predictions of separate elements.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together in a low-fidelity setup.
5	Component and/or breadboard validation in a relevant environment.	Fidelity increases significantly; components are integrated with reasonably realistic supporting elements and tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	A major step in readiness; a representative model or prototype is tested in a high-fidelity lab or simulated operational environment.
7	System prototype demonstration in an operational environment.	An actual system prototype is demonstrated in an operational environment (e.g., in a vehicle, on an aircraft).
8	Actual system completed and qualified through test and demonstration.	The technology is proven to work in its final form and under expected conditions; the end of true system development.
9	Actual system proven through successful mission operations.	The technology is applied in its final form and under actual mission conditions.
Source: Adapted from DoD Technology Readiness Assessment Guidebook, Feb 2025 ⁵		

The software TRLs follow a similar path of increasing integration and environmental realism, moving from algorithms and modules to fully integrated software packages demonstrated under operational loads and security conditions.⁵

Critical Technology Elements (CTEs)

The focus of any TRA is on the **Critical Technology Elements (CTEs)**. A CTE is defined as a new or novel technology on which a program or platform depends to successfully develop a system or meet an operational threshold.⁵ It is the element that poses a major technological risk during design or demonstration. Early and accurate identification of CTEs is fundamental to the entire TRA process, as these are the specific components whose maturity must be rigorously assessed and tracked.⁵



The Formal TRA Process

The DoD, incorporating best practices from the Government Accountability Office (GAO), outlines a formal five-step process for conducting a high-quality TRA. This structured approach ensures the assessment is credible, objective, reliable, and useful.⁵

1. **Step 1: Establish a TRA Plan and Select a TRA Team:** Define the scope, goals, and resources for the assessment. Assemble an independent team of subject matter experts (SMEs) with relevant experience.
2. **Step 2: Identify Critical Technology Elements:** The SME team, in consultation with the program manager, identifies the CTEs based on a comprehensive review of the system design, performance requirements, and potential risks.
3. **Step 3: Assess Critical Technology Elements:** The team evaluates the evidence for each CTE—test data, analytical reports, schematics—against the TRL criteria to assign a maturity level.
4. **Step 4: Prepare the TRA Report:** The findings, rationale, supporting evidence, and any dissenting opinions are documented in a formal report.
5. **Step 5: Use the TRA Report Findings:** The report informs leadership, guides decision-making on resource allocation, and serves as the basis for developing a Technology Maturation Plan (TMP) for any immature CTEs.⁵

This rigorous process is the mechanism that transforms the TRL scale from a simple set of definitions into a powerful, defensible tool for risk management.

Manufacturing Readiness Levels (MRLs): Assessing "Can We Build It?"

While TRLs assess if a technology can perform its function, MRLs assess if that technology can be manufactured reliably, affordably, and at the required scale.¹ MRLs are a complementary framework designed to evaluate the maturity of a technology from a manufacturing perspective, answering critical questions that TRLs do not address: Is it producible? What will it cost? Are the materials and suppliers available? Can it be made in a production environment?¹

The 2025 MRL Deskbook Standard

The DoD's *Manufacturing Readiness Level (MRL) Deskbook, Version 2025* provides the standard for MRL assessments.⁵ The framework uses a 10-level scale, with each level representing a greater degree of manufacturing maturity and a corresponding reduction in manufacturing risk. Similar to TRLs, the MRL scale tracks progress through increasingly realistic manufacturing environments: from a **Laboratory Environment** (MRL 4), to a **Production-Relevant Environment** (MRL 5-6), to a **Production-Representative Environment** (MRL 7), and finally to a demonstrated **Pilot Line** (MRL 8) and full production.⁵



Table 2: DoD Manufacturing Readiness Level Definitions (2025)

MRL	Definition
1	Basic manufacturing implications identified.
2	Manufacturing concepts identified.
3	Manufacturing proof of concept developed.
4	Capability to produce the technology prototype in a laboratory environment.
5	Capability to produce prototype components in a production-relevant environment.
6	Capability to produce a prototype system or subsystem in a production-relevant environment.
7	Capability to produce systems, subsystems, or components in a production-representative environment.
8	Pilot line capability demonstrated; ready to begin Low-Rate Initial Production (LRIP).
9	Low-rate production demonstrated; capability in place to begin Full-Rate Production (FRP).
10	Full-Rate Production demonstrated and lean manufacturing practices in place.
Source: Adapted from DoD Manufacturing Readiness Level (MRL) Deskbook, 2025 ⁵	

The Nine MRL "Threads"

A crucial aspect of the MRL framework is its multi-dimensional nature. An MRL assessment is not a single score but an integrated evaluation across nine distinct "threads," each representing a core dimension of manufacturing readiness. A shortfall in any one of these threads can jeopardize the entire production effort. This comprehensive view is what makes the MRL framework so powerful for identifying and managing manufacturing risk.²

Table 3: The Nine MRL Threads

Thread	Description
Technology and Industrial Base	Analyzes the capability of the Defense Industrial Base (DIB) to support the entire lifecycle of the system.
Design	Assesses the producibility, maturity, and stability of the system design and its impact on manufacturing.
Cost and Funding	Examines the adequacy of funding and the risks associated with achieving manufacturing cost targets.



Materials	Analyzes risks associated with all materials, including availability, supply chain maturity, and special handling.
Process Capability and Control	Determines if manufacturing processes are mature, stable, and capable of meeting design intent and quality requirements.
Quality	Assesses the risks and management efforts in place to control quality and foster continuous improvement.
Manufacturing Workforce	Evaluates the required skills, availability, and number of personnel needed for the manufacturing effort.
Facilities	Analyzes the capabilities and capacity of all key manufacturing facilities, from prime contractors to suppliers.
Manufacturing Management	Assesses the orchestration of all elements needed to translate the design into a fielded system, meeting affordability and availability goals.
Source: Adapted from DoD Manufacturing Readiness Level (MRL) Deskbook, 2025 ⁵	

The TRL-MRL Interdependency: A Symbiotic and Perilous Relationship

While TRLs and MRLs are distinct frameworks, they are inextricably linked. The successful transition of a technology from lab to market depends on the concurrent maturation of both its technical performance and its manufacturability.²

Notional Congruence, Practical Divergence

The MRL scale was designed to be "roughly congruent" with the TRL scale to facilitate synergy and ease of use.² For example, achieving TRL 6 (prototype demonstration in a relevant environment) is notionally aligned with achieving MRL 6 (capability to produce that prototype in a production-relevant environment). However, in practice, technology and manufacturing maturity often progress at different rates.⁵ A common and dangerous failure mode occurs when a technology achieves a high TRL in a laboratory setting (e.g., a scientist successfully demonstrates a novel chemical process in glassware), while the manufacturing processes required to produce it at scale remain completely undeveloped (e.g., no industrial-scale reactors exist, and key precursors are unavailable commercially). This creates a significant and often underestimated risk gap.

Causality and Pacing

The relationship is not merely correlational; it is causal. Manufacturing readiness is fundamentally *paced* by technology readiness and design stability.² It is impossible to mature and stabilize a manufacturing process (e.g., optimize yields, establish statistical process control) for a product whose design is still in flux. A change in the core technology or design specifications can render previous manufacturing development obsolete. Therefore, achieving a sufficient level of



technological maturity (a high TRL) is a necessary, but not sufficient, condition for advancing manufacturing maturity (a high MRL).

This dynamic requires a proactive and integrated management approach. A purely sequential strategy—first perfecting the technology to TRL 9 and only then considering manufacturing—is a recipe for failure. It leads to discovering insurmountable manufacturing challenges far too late in the development cycle, resulting in massive cost overruns, schedule delays, or outright project cancellation. Instead, a concurrent engineering approach is required, where manufacturing considerations are integrated into the technology development process from the very beginning. The MRL framework provides the structure for this integration, forcing teams to consider producibility, material supply chains, and cost targets long before a final design is locked. This "look-ahead" principle is a critical element of successful technology commercialization. For instance, even while a project is at TRL 4 (lab validation), a forward-looking MRL assessment can identify critical manufacturing gaps—such as the need to develop a novel piece of processing equipment or qualify a new supplier for a critical raw material—that must be incorporated into the Technology Maturation Plan (TMP) to ensure a smooth transition to later stages.⁵

Application in the Critical Minerals Sector: A High-Stakes Environment

The TRL and MRL frameworks are not just theoretical constructs; they are essential strategic tools for navigating the unique and formidable challenges of the critical minerals processing industry. In a sector defined by high capital costs, long timelines, and intense geopolitical pressure, these readiness assessments provide the structure for de-risking projects and making them viable for both public and private investment.

The Strategic Imperative and Inherent Risks of the Midstream

The United States' economic and national security is increasingly reliant on a stable supply of critical minerals such as rare earth elements (REEs), lithium, cobalt, nickel, and graphite.⁶ These materials are indispensable inputs for a vast array of modern technologies, from consumer electronics and electric vehicles to advanced defense systems and renewable energy infrastructure.⁸

The Geopolitical Context and Domestic Processing Bottleneck

A stark vulnerability exists in the current global supply chain: while mineral extraction is geographically diverse, the midstream processing—the complex steps of refining, separating, and purifying raw ores into high-value materials—is overwhelmingly dominated by foreign entities, particularly China.⁶ China controls an estimated 80-90% of the global processing capacity for key minerals like REEs.⁸ This concentration creates a significant bottleneck and exposes the U.S. to profound supply chain risks, including politically motivated export restrictions and price manipulation.⁶



Addressing this vulnerability requires building a robust domestic midstream processing industry. The primary challenge is not a lack of domestic mineral resources, which can be sourced from traditional mines as well as non-traditional feedstocks like coal ash and mine waste, but a severe deficit in the industrial capacity to transform these raw materials into usable forms.⁸

Startup Challenges in a Capital-Intensive Sector

Startups and innovators aiming to fill this processing gap face a perfect storm of commercialization challenges that make the sector notoriously difficult to penetrate:

- **High Capital Intensity:** Unlike software or biotech, mineral processing requires massive capital investment in physical infrastructure. Building even a pilot-scale facility can cost tens of millions of dollars, while a commercial-scale plant can run into the hundreds of millions or billions.¹²
- **Long Project Lead Times:** The timeline from initial discovery or process invention to a fully operational mine and processing plant can average 15 to 20 years, a significant increase from previous decades.¹⁴ This long, pre-revenue period is a major deterrent to traditional venture capital.
- **Technical and Scale-Up Risk:** Scaling a chemical process from a laboratory beaker to an industrial reactor is non-linear and fraught with risk. Issues in heat transfer, mass balance, and materials handling that are trivial at the bench scale can become project-killing obstacles at the pilot or commercial scale.
- **Market and Economic Uncertainty:** Critical mineral prices are notoriously volatile, making it difficult to create bankable financial models.¹² Furthermore, startups must compete with established, often state-subsidized, international players who can leverage economies of scale and different regulatory standards to maintain a cost advantage.¹¹
- **Regulatory and Permitting Hurdles:** Mining and chemical processing projects are subject to extensive and often lengthy environmental and permitting reviews, which can add years and significant cost to a project timeline.¹⁴

TRL/MRL as an Investment and De-Risking Tool for Critical Minerals

Given this high-risk environment, the TRL and MRL frameworks have become the indispensable language of due diligence and project management for all serious stakeholders in the sector.

Government Funding and Due Diligence

The U.S. Department of Energy (DOE), through its Advanced Materials and Manufacturing Technologies Office (AMMTO) and other programs, is deploying billions of dollars via legislation like the Bipartisan Infrastructure Law to catalyze the development of a domestic critical minerals supply chain.¹⁷ These funding opportunities are explicitly structured to move technologies through the readiness levels, from bench-scale R&D to pilot, demonstration, and commercial-scale facilities.¹⁷

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For major DOE projects, the Technology Readiness Assessment (TRA) and Technology Maturation Plan (TMP) are formal requirements tied to the "Critical Decision" (CD) gate-review process.¹⁹ For example, DOE guidance recommends that all CTEs should reach at least TRL 4 before CD-1 (Alternative Selection) and TRL 6 before CD-2 (Approve Performance Baseline).¹⁹ This structured approach forces project teams to systematically de-risk their technology and provides the government with a clear, evidence-based methodology for making funding decisions.

Investor Perspective and Structuring the Roadmap

For private investors—from venture capital to project finance—TRL and MRL assessments are the cornerstone of technical due diligence. They provide a standardized, objective framework to quantify the immense risks inherent in the sector.²¹ A startup presenting a novel extraction technology without a credible, third-party-validated TRL assessment and a detailed plan for MRL progression is considered fundamentally un-investable.

Consequently, the TRL/MRL framework provides the very structure of a startup's commercialization roadmap. Key milestones are not defined by time but by the achievement of specific readiness levels. A credible roadmap will outline the specific experiments, prototype builds, and pilot operations required to advance from one level to the next, along with the associated costs and timelines. This transforms a vague "plan to scale" into a concrete, stage-gated development plan that investors can evaluate and fund incrementally.

Navigating the Gauntlet of Scale-Up: The Valley of Death and the McNulty Curve

The path from a laboratory breakthrough to a profitable commercial plant is not a smooth, linear progression. It is a gauntlet of distinct challenges, each with its own set of risks and capital requirements. The TRL/MRL frameworks help to define these stages, with the most notorious being the "valley of death." Successfully navigating this valley is a prerequisite for tackling the final challenge: the production ramp-up, whose success or failure is starkly illustrated by the McNulty curve.

The Valley of Death (TRL 4-7 / MRL 4-7): The Chasm Between Lab and Pilot

The "valley of death" is a widely recognized term in technology commercialization that describes the critical funding and development gap between early-stage, publicly funded research and later-stage, privately funded commercialization.²³ In the context of the readiness frameworks, this chasm typically spans from TRL 4 to TRL 7.⁴

Defining the Gap

A technology at TRL 4 has been validated at the component or breadboard level in a laboratory. The fundamental science works.⁵ However, it is a long way from being a commercially viable product. To cross the valley of death, the technology must be scaled up, integrated into a system prototype, and



demonstrated in a relevant or operational environment to achieve TRL 7.⁴ This is the phase where the focus shifts from pure science to applied engineering, and it is where most promising technologies fail.²⁵

Why the Valley is a Killer for Minerals Startups

While the valley of death is a challenge for all technology sectors, it is a particularly deep and treacherous chasm for startups in capital-intensive industries like critical minerals processing. For a software company, bridging this gap might involve building a beta version of an app—a process that might cost a few million dollars. For a critical minerals startup, bridging the same TRL 4-7 gap requires designing, constructing, and operating an integrated pilot plant. This is a multi-year effort that can easily cost tens to hundreds of millions of dollars, all before a single dollar of revenue is generated.¹²

This immense capital requirement creates a severe funding gap. Government research grants typically end at TRL 3 or 4, while traditional venture capital and private equity are often hesitant to invest such large sums in a project that still carries significant technical risk.²² This funding gap is the primary filter that eliminates the vast majority of promising mineral processing technologies before they ever have a chance to prove their commercial viability.²⁷

Bridging the Valley: The Integrated TRL/MRL Challenge

Successfully crossing the valley of death requires more than just capital; it requires a systematic de-risking of the technology and its associated manufacturing processes. It involves generating the robust data package needed to prove to investors and customers that the process is not just scientifically sound but also technically and economically viable at scale. This means achieving both TRL and MRL milestones concurrently.

- **Achieving TRL 7:** This requires demonstrating a system prototype in an operational environment. For a processing technology, this means building and running an integrated pilot plant that processes real-world feedstock under realistic conditions for an extended period (e.g., 1,000+ hours) to prove process stability, reliability, and performance.⁵
- **Achieving MRL 5-7:** This parallel effort involves demonstrating the capability to produce prototype components in a **production-relevant environment** and then systems in a **production-representative environment**.⁵ This translates to validating key unit operations, qualifying suppliers for critical reagents, developing initial quality control procedures, and proving that the equipment used in the pilot plant is a scalable representation of the future commercial facility.

The Production Ramp-Up (MRL 7-10) and the McNulty Curve

For the few projects that successfully secure funding and navigate the valley of death to build a commercial-scale plant, a final, formidable challenge remains: the production ramp-up. The McNulty curve, an empirical framework developed from decades of case studies in the mining and



metallurgical industries, serves as a powerful diagnostic tool for benchmarking the success of this critical phase.²⁹

The Four "Series" of Ramp-Up Performance

The McNulty curve plots the actual production rate as a percentage of the plant's design capacity over time, starting from commissioning. The analysis of dozens of projects revealed four distinct patterns, or "Series," of ramp-up performance.²⁹

- **Series 1 (Excellent):** These projects exhibit a rapid and smooth ramp-up, typically achieving 80-100% of design capacity within the first 6-12 months. They represent best-in-class project execution and technology implementation.²⁹
- **Series 2 (Average):** These projects experience some technical or operational hurdles, leading to a slower ramp-up that may take 18-24 months to approach design capacity. This is a common outcome.
- **Series 3 (Difficult):** These projects are plagued by significant design flaws, equipment failures, or process instabilities. They struggle for years to reach even 50-60% of design capacity and often require significant additional capital investment to fix fundamental problems.
- **Series 4 (Disaster):** These projects represent a catastrophic failure. They are unable to overcome fundamental technical or operational flaws and never come close to achieving their design capacity, often resulting in complete project failure and write-off.

The financial implications are stark. A Series 1 project begins generating positive cash flow quickly, delivering returns to investors as planned. A Series 3 or 4 project becomes a "cash bonfire," destroying value and often leading to bankruptcy.³³

Key Characteristics Influencing Performance

The most crucial finding from McNulty's research is that a project's ramp-up performance is not a matter of luck during commissioning; it is predetermined by the quality of the work done in the development phases long before construction begins. The characteristics most strongly correlated with a successful, Series 1 ramp-up include:

- **Use of Mature Technology:** The core process technology is well-understood and has been proven at a relevant scale.
- **Thorough Pilot-Scale Testing:** The process has been extensively tested on representative feed materials in a pilot plant, and all potentially risky unit operations have been de-risked.
- **Experienced Team:** The project is led by an experienced and committed management and technical team.
- **Informed Workforce:** The operations team is well-educated and trained on the new process before startup.²⁹

Conversely, projects that fall into Series 3 or 4 are often characterized by the use of unproven technology, incomplete or non-existent pilot testing, and inexperienced teams.²⁹



Integrating the Frameworks: A Predictive Model for Success

The true strategic value of these frameworks emerges when they are integrated. The McNulty curve is not an independent phenomenon; it is a direct, lagging indicator of how well a project navigated the TRL/MRL progression, particularly through the valley of death. The work done to de-risk a technology between TRL 4 and TRL 7 directly sets the stage for its ultimate ramp-up performance.

This establishes a powerful predictive model. The prerequisites for a "Series 1" McNulty outcome—"mature technology" and "detailed pilot scale testing"—are precisely what is achieved by rigorously advancing a technology to TRL 7 and MRL 8.

1. A **"mature technology"** in the context of a new plant is one that has been de-risked and proven in an operational environment. This is the definition of **TRL 7** ("System prototype demonstration in an operational environment").⁵
2. **"Detailed pilot scale testing"** is the very work required to demonstrate that the manufacturing process is understood and ready for low-rate production. This is the definition of **MRL 8** ("Pilot line capability demonstrated; ready to begin LRIP").⁵
3. The entire journey of designing, funding, building, and operating a pilot plant to generate the data to validate the process and design the commercial facility is the act of crossing the valley of death.
4. Therefore, a startup that successfully crosses the valley of death by diligently achieving TRL 7 and MRL 8 has, by definition, established the essential preconditions for a Series 1 ramp-up. Conversely, a company that shortcuts this critical phase—by relying on incomplete lab data, skipping the integrated pilot stage, or using non-representative feedstock—is pre-ordaining itself for a difficult and costly Series 3 or 4 outcome.

This transforms the TRL/MRL framework from a simple maturity scorecard into a powerful predictive tool for a project's ultimate financial success. For investors and project developers, a rigorous assessment of a project's status within the TRL 4-7 / MRL 4-8 range provides the most reliable forecast of its future production performance and return on investment.

Strategic Partnership for Commercialization: The Role of delta3coretec

The preceding analysis demonstrates that successfully scaling a critical minerals processing technology is a multi-dimensional challenge requiring the concurrent maturation of technology, manufacturing processes, and commercial strategy. Navigating this complexity demands specialized expertise that bridges the gap between scientific discovery, process engineering, and market reality. A specialized consultancy like delta3coretec is positioned as a strategic partner capable of guiding startups and investors through these integrated challenges, from initial concept to full-scale commercial production.³⁴



De-Risking the Roadmap (TRL 1-4 / MRL 1-4): Techno-Economic Analysis

The journey to commercialization begins long before the first pilot plant is built. The foundational decisions made at the earliest stages of research and development (TRL 1-4) have an outsized impact on the ultimate viability of a project.

- **The Problem:** Many technology-driven startups fall into the trap of focusing exclusively on technical performance in the laboratory (achieving a high TRL for the core science) while neglecting critical early-stage manufacturing and commercial considerations. They may develop a process that works beautifully at the bench scale but is economically non-viable due to expensive reagents, low yields, or the production of an off-spec product. This failure to align R&D with market realities corresponds to neglecting the "Cost & Funding" and "Design" threads of the MRL framework at their earliest, most crucial stages.⁵
- **delta3coretec's Solution:** The firm offers to build an investable, market-aligned commercialization roadmap from the outset through rigorous **Techno-Economic Analysis (TEA)**.³⁴ By integrating process modeling with market data and financial analysis from day one, they ensure that the technology being developed is aimed at a real market need with a specific product specification and a plausible manufacturing cost structure. This proactive approach prevents wasted R&D on a technology that, while scientifically interesting, may have no path to profitability. It grounds the entire development plan in commercial reality, creating a credible and investable roadmap.

Bridging the Valley of Death (TRL 4-7 / MRL 4-7): Process Scale-Up

The valley of death represents the most capital-intensive and technically challenging phase of commercialization. It is where the theoretical process must be translated into a functional, integrated physical plant.

- **The Problem:** Moving from a lab beaker (TRL 4) to an integrated pilot plant (TRL 7) is a non-linear scaling challenge. Startups often lack the deep process engineering and modeling expertise to design a pilot plant that is both effective for data collection and a valid representation of a future commercial facility. This leads to costly design errors, extended timelines, and a failure to generate the high-quality data needed to secure the much larger funding required for a commercial plant.
- **delta3coretec's Solution:** The firm specializes in **Process Scale-Up**, utilizing advanced simulation tools like SysCAD and digital twins to design and optimize scalable production systems.³⁴ Instead of relying solely on expensive and time-consuming physical trial-and-error, their simulation-first approach allows for the rapid iteration of process flowsheets, mass and energy balances, and equipment sizing. This methodology accelerates the journey to TRL 7 and MRL 7 by:
 1. Optimizing the process design *before* capital is spent on steel.
 2. Identifying and mitigating potential scale-up issues (e.g., thermal management, mixing inefficiencies) in a virtual environment.
 3. Generating a robust, defensible engineering data package that is essential for securing the



tens of millions of dollars in financing required for a physical pilot plant.

Ensuring a "Series 1" Ramp-Up (TRL 8-9 / MRL 8-10): QA/QC and Supply Chain

Successfully operating a pilot plant (achieving MRL 8) is a monumental achievement, but it is not the final goal. The ultimate objective is to achieve a rapid, efficient, and profitable ramp-up to full-scale production (MRL 9-10), as characterized by a McNulty Series 1 curve.

- **The Problem:** The transition from a pilot operation run by PhDs to a full-scale commercial plant run by operators requires a profound shift in focus towards manufacturing discipline. This includes establishing rigorous quality assurance and quality control (QA/QC) systems to meet demanding customer specifications (e.g., for battery-grade materials) and building a resilient supply chain for raw materials. Failures in these areas are primary causes of ramp-up delays and Series 3 or 4 outcomes.
- **delta3coretec's Solution:** Leveraging the deep operational experience of its leadership, including a former CTO of a successful synthetic graphite scale-up, delta3coretec implements the disciplined systems required for commercial success.³⁴ Their **QA/QC Implementation** service establishes the frameworks to ensure product consistency and quality, directly addressing the MRL "Quality" thread. Simultaneously, their expertise in building **resilient non-Chinese supply chains** addresses the "Materials" thread. By putting these critical manufacturing management systems in place before commercial production begins, they effectively engineer the project to achieve a best-in-class Series 1 ramp-up, ensuring the technology not only works but can be produced reliably and profitably at scale.

Conclusion and Strategic Recommendations

The journey to establish a domestic critical minerals processing industry is a strategic imperative, but the path for individual companies is a gauntlet of technical, manufacturing, and financial hurdles. This analysis has demonstrated that the integrated use of Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) frameworks is not merely a bureaucratic requirement but the essential methodology for navigating this complex landscape. The progression through these readiness levels, particularly the successful transit of the TRL 4-7 "valley of death," is a direct and powerful predictor of a project's ultimate commercial success as measured by the production ramp-up performance of the McNulty curve.

The key takeaway is that technological innovation alone is insufficient. Success in the critical minerals sector requires a concurrent and disciplined maturation of the technology, its associated manufacturing processes, and its underlying commercial strategy. The TRL and MRL frameworks provide the indispensable language and structure for managing this integrated process.

Based on this analysis, the following strategic recommendations are offered to key stakeholders:

- **For Startups and Innovators:**
 - **Integrate TRL and MRL from Day One:** Treat these frameworks not as compliance



exercises for funding applications, but as the central pillar of your technical and commercialization strategy.

- **Invest in Process Modeling Early:** Utilize process simulation tools during the R&D phase (TRL 3-4) to build a robust techno-economic model. This will ensure your lab work is aimed at a commercially viable target and will accelerate the design of your pilot plant.
- **Do Not Shortcut the Pilot Stage:** The data generated from a well-designed, integrated pilot plant (the journey to TRL 7 / MRL 8) is the most valuable asset you can create. It is the primary vehicle for de-risking the technology for investors and securing the financing needed for commercial scale-up.
- **For Investors (Venture Capital, Private Equity, Project Finance):**
 - **Mandate Rigorous TRL/MRL Assessments:** Insist on independent, third-party TRL and MRL assessments as a core component of technical due diligence. A startup's ability to articulate and execute a credible TRL/MRL maturation plan is a strong indicator of its management and technical competence.
 - **Use Readiness Levels as a Leading Indicator:** View a project's progress through the TRL 4-7 valley of death as a leading indicator of its future ramp-up performance. A project that successfully achieves TRL 7 and MRL 8 has fundamentally de-risked the key variables that lead to a successful "Series 1" McNulty outcome.
 - **Fund for the Valley:** Recognize that the pilot/demonstration phase is the most critical and capital-intensive hurdle. Structure financing tranches around the achievement of specific TRL/MRL milestones to align investment with tangible risk reduction.
- **For Policymakers and Government Agencies (DOE, DoD):**
 - **Strengthen TRL/MRL Requirements in Funding:** Continue to align federal funding opportunities with TRL/MRL milestones, ensuring that public funds are deployed to systematically mature technologies through the development lifecycle.
 - **Support Shared Pilot Facilities:** The high cost of pilot plants is a major barrier. Consider funding shared, multi-user pilot facilities at national labs or through public-private partnerships. This would allow multiple startups to test and de-risk their technologies at a fraction of the cost of building individual plants, significantly lowering the barrier to entry and accelerating innovation.
 - **Foster Expertise:** Support training and development programs that build a workforce of engineers and project managers skilled in applying TRL, MRL, and other advanced manufacturing principles to the unique challenges of the critical minerals sector.

By embracing a disciplined, integrated approach to technology and manufacturing readiness, all stakeholders can work to mitigate the immense risks of the scale-up gauntlet, increase the success rate of new ventures, and accelerate the establishment of a secure and resilient domestic critical minerals supply chain.



Appendix: TRL/MRL Self-Assessment Cheat Sheet for Critical Minerals Processing

Stage	TRL Level & Definition	MRL Level & Definition	Key Objective for Minerals Processing	Required Evidence & Activities	Next Target Milestone
I. R&D	TRL 1: Basic principles observed.	MRL 1: Basic manufacturing implications identified.	Identify and screen novel chemical pathways or process concepts.	• Literature review & patent search • Theoretical calculations • Initial market assessment	Formulate a specific technology concept.
(Lab/Bench)	TRL 2: Technology concept formulated.	MRL 2: Manufacturing concepts identified.	Define a conceptual process flowsheet and identify key chemical reactions.	• High-level process flow diagram (PFD) • Preliminary mass & energy balance • Identification of major reagents & feedstocks	Secure funding for experimental proof-of-concept.
	TRL 3: Analytical & experimental proof of concept.	MRL 3: Manufacturing proof of concept developed.	Demonstrate the core chemical reaction(s) work at the bench scale.	• Lab notebook data validating core reaction • Initial assay results of product • Identification of key process variables (temp, pressure, pH)	Validate integrated components in a lab setup.
	TRL 4: Component/breadboard validation in a lab environment.	MRL 4: Capability to produce in a lab environment.	Validate the integrated process flowsheet at the bench scale and produce gram-scale samples.	• Operation of a bench-scale, semi-integrated apparatus • Mass-energy balance from experimental data • Preliminary Techno-Economic	Secure funding for mini-pilot / scaled-up component testing.



				Analysis (TEA) • Initial list of potential suppliers for key reagents	
II. Pilot & Demo	TRL 5: Component/breadboard validation in a relevant environment.	MRL 5: Capability to produce prototype components in a production-relevant environment.	Test scaled-up individual unit operations (e.g., leaching reactor, SX circuit) with representative feedstock.	• Data from scaled-up, non-integrated unit operation tests • Updated TEA with experimental data • Initial supplier qualification & material spec sheets • Preliminary pilot plant P&ID	Design and secure funding for an integrated pilot plant.
("The Valley")	TRL 6: System/prototype demonstration in a relevant environment.	MRL 6: Capability to produce a prototype system in a production-relevant environment.	Operate a fully integrated, continuous mini-pilot plant in a lab or skid-mounted setup.	• Data from continuous, integrated mini-pilot operation • Detailed pilot plant P&ID and equipment list • HAZOP and risk assessment for pilot plant • Bankable TEA and financial model	Finalize engineering and begin construction of the pilot plant.
	TRL 7: System prototype demonstration in an operational environment.	MRL 7: Capability to produce in a production-representative environment.	Construct and commission the pilot plant; begin sustained operations to generate product for customer qualification.	• Pilot plant construction complete & commissioned • Standard Operating Procedures (SOPs) developed • Initial QA/QC data from pilot production • Product	Achieve steady-state operation and secure customer qualification.



				samples sent to potential customers	
III. Commercial	TRL 8: Actual system completed and qualified through test and demonstration.	MRL 8: Pilot line capability demonstrated; ready for LRIP.	Achieve steady-state pilot plant operation, meet all customer specs, and generate a full engineering data package for commercial plant design.	•Sustained pilot campaign data (>1,000 hours) •Customer qualification approval •Finalized commercial plant Front-End Engineering Design (FEED) package •Long-lead equipment identified and quoted	Secure full project financing for the commercial plant.
(Scale-Up)	TRL 9: Actual system proven through successful mission operations.	MRL 9: Low-rate production demonstrated; ready for FRP.	Construct, commission, and begin ramp-up of the first commercial plant (or first production train).	• Commercial plant mechanically complete •Commissioning and startup of commercial plant •Production data showing ramp-up vs. plan (McNulty Curve) • Supply chain and logistics are operational	Achieve nameplate capacity and positive cash flow.
		MRL 10: Full-Rate Production demonstrated and lean practices in place.	Achieve stable, profitable production at or above nameplate capacity and implement continuous improvement programs.	•Sustained production at target rates and costs •Statistical Process Control (SPC) data •Lean manufacturing/ Six Sigma	Expand capacity and/or develop next-generation products.



				projects initiated •Established supply chain and customer relationships	
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