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Critical Mineral & Material Research at NIST: A Review and Future Directions

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Abstract

The United States is actively addressing significant challenges in securing a reliable supply of Critical Minerals and Materials (CMMs) essential to modern technology and national security. With 63 unique CMMs currently identified by the U.S. Geological Survey and U.S. Department of Energy as having high supply-chain risk, the federal government is responding to bridge historical gaps in the domestic value chain. As the national metrology institute, NIST supports this federal effort by advancing the measurement science, standards, and data infrastructure that underpins a resilient domestic supply chain. Following a July 2025 internal workshop, this report synthesizes NIST's active research and potential capabilities across four key pillars: material substitution, traceability, characterization, and recovery. These strategic efforts establish foundational benchmarks to accelerate domestic adoption, de-risk supply chains, and ensure U.S. manufacturing competitiveness.

Keywords

Additive Manufacturing; Circular Economy; Critical Minerals and Materials; Digital Infrastructure; Material Substitution; Metrology; Standard Reference Materials; Supply Chain Resilience; Traceability.

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Executive Summary

The U.S. faces significant challenges in securing a reliable supply of Critical Minerals and Materials (CMMs) essential to modern technologies and national security. Currently, 63 unique CMMs have been identified by the U.S. Geological Survey (USGS) and U.S. Department of Energy (DOE), representing a diverse range of elements and engineered materials with high supply-chain risk. The National Institute of Standards and Technology (NIST) is uniquely positioned to address CMM challenges through its core mission of promoting U.S. innovation and industrial competitiveness. By advancing measurement science, standards, and data infrastructure, NIST provides the technical foundation necessary to enhance economic security and ensure the reliability of the domestic CMM value chain.

In July 2025, NIST convened an internal workshop that brought together experts from across its laboratories to share existing activities and capabilities, as well as discuss areas where NIST can make a meaningful impact. This report synthesizes those findings, highlighting how NIST's measurement science, data infrastructure, reference materials, and standards leadership underpin a more resilient, circular domestic supply chain.

Current NIST Activities

NIST currently addresses CMM challenges across four key areas:

- Substitution and Alternatives: Developing databases and autonomous experimentation to support the discovery of CMM-free or -lean materials.
- Traceability and Market Dynamics: Advancing measurement methods, models, and data systems to track the flow of material(s) through supply chains.
- Identification, Characterization, and Quantification: Enhancing methods and scientific instrumentation to analyze primary and secondary feedstocks.
- Separation and Recovery: Establishing the metrological foundation for extracting high-value CMMs.

Strategic Future Directions

NIST could deepen and expand its impact on addressing CMM challenges by prioritizing research activities that integrate data infrastructure, instrument and methods development, and metrology that bridge the gap between bench-scale research and industrial implementation. To achieve this, NIST could focus on the following integrated directions:

- Modernize and Expand Data Infrastructure: Provide a modern, complex data library focusing on computationally intensive CMM material properties and microstructure. This digitally compatible infrastructure would support AI/ML workflows, enabling manufacturers to rapidly minimize CMM reliance and maximize recovery.
- Develop Field-Deployable Analytical Instruments: Advance real-time, high-precision instruments to characterize material inputs in complex extraction and recycling streams. These instruments would empower stakeholders to rapidly qualify materials and identify valuable CMMs.

- Accelerate Substitution and Alternatives Discovery: Accelerate material substitutions by integrating predictive modeling with autonomous experimentation within a design-led framework. This approach targets critical data gaps, providing technical evidence needed to de-risk and deploy CMM-free or -lean alternatives.
- Establish an Industry Consortium for CMM Recovery: Convene recyclers and manufacturers to drive pre-competitive research and harmonize purity tolerances. This would help establish the technical foundation and quality assurance needed for the wide-scale industrial adoption of recycled content.
- Develop and Recertify Standard Reference Materials (SRMs): Streamline the creation of new physical standards (artifacts) and recertify existing matrix SRMs to ensure measurement accuracy and traceability across the CMM value chain. This would enable manufacturers to move from prototype to full-scale production with confidence.

By pursuing these research directions, NIST would help the U.S. industrial base transition toward a more resilient, circular supply chain. This strategic alignment ensures that high-fidelity data and validated benchmarks are available to empower manufacturers to innovate, substitute, and recover materials with precision and confidence, ultimately promoting a more resilient and circular CMM supply chain.

1. Introduction

Critical minerals and materials are essential to modern economies and national security, yet they are defined by significant supply chain risks and regional dependencies. In the U.S., the Energy Act of 2020 [1] mandates that the U.S. Department of the Interior (via the USGS) and the U.S. DOE identify these resources based on their respective roles in the broader U.S. economy and the energy sector. Under this framework, critical minerals and materials are defined as shown in the text box below.

The USGS identifies critical minerals by assessing current and historical supply risks to national security and the broader economy [2]. In contrast, the DOE uses forward-looking forecasting to identify materials essential to the energy sector, including both raw minerals and engineered materials – highly processed or synthesized substances like silicon carbide. Despite these differing scopes, the lists exhibit some overlap due to a shared focus on supply chain vulnerability (Figure 1).

Criticality is a dynamic status, and, consequently, the Energy Act requires periodic updates to these lists to reflect changes in domestic and global markets. The published 2025 List of Critical Minerals [3] recently expanded the registry from 50 to 60 commodities, while DOE's most recent list was published in 2023. Figure 1 presents the two lists, displaying the commodities unique to each list as well as present on both. For this report, critical minerals and materials are collectively referred to as CMMs.

The Energy Act of 2020 defines Critical Materials and Critical Minerals as:

Critical Material:
Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines:
- (i) has a high risk of a supply chain disruption; and
- (ii) serves an essential function in 1 or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or

A critical mineral (as designated by the Secretary of the Interior).

Critical Mineral:
Any mineral, element, substance, or material designated by the Secretary of the Interior that:
- (i) are essential to the economic or national security of the United States;
- (ii) the supply chain of which is vulnerable to disruption (including restrictions associated with foreign political risk, abrupt demand growth, military conflict, violent unrest, anti-competitive or protectionist behaviors, and other risks throughout the supply chain); and
- (iii) serve an essential function in the manufacturing of a product (including energy technology-, defense-, currency-, agriculture-, consumer electronics-, and health care-related applications), the absence of which would have significant consequences for the economic or national security of the United States

The term does not include fuel minerals; water, ice, or snow; or common varieties of sand, gravel, stone, pumice, cinders, and clay

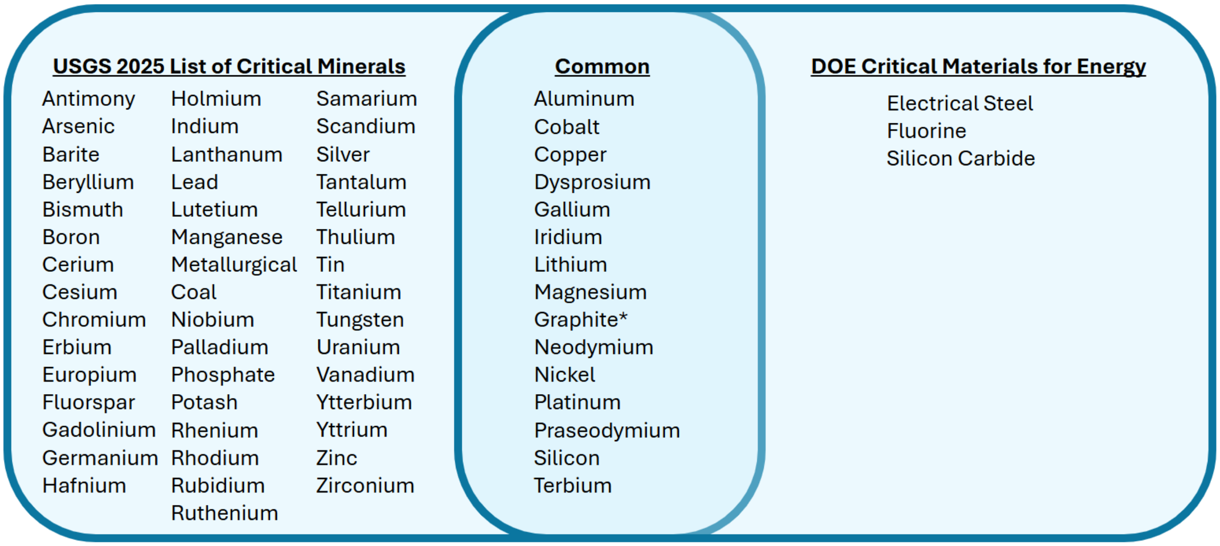

Figure 1: Comparison of the USGS Critical Minerals and DOE Critical Materials lists [3][4] *Graphite includes natural graphite as described by the DOE and both natural and synthetic graphite as evaluated by the USGS.

Combined, there are currently 63 unique CMMs identified by the USGS and DOE, including the 60 mineral commodities on the 2025 USGS list, such as rare earth elements (REEs), platinum group metals (PGMs), lithium, and other key metals, as well as specialized engineered materials – such as electrical steel and silicon carbide – tracked by the DOE. These substances are prioritized because of their essential roles in everything from defense systems and telecommunications to advanced grid infrastructure and electric vehicle manufacturing.

To mitigate supply risks, the U.S. government is advancing efforts to build a resilient, secure domestic CMM supply chain. Legislative efforts, like the "Critical Mineral Dominance Act" (H.R. 4090) [5] aim to codify several recent Executive Orders (EOs 14154, 14241, and 14272) designed to bolster industrial resilience [6], [7], [8]. These are supported by 2026 initiatives such as Project Vault [9], a public-private partnership aimed at creating a strategic minerals stockpile, and the Forum on Resource Geostrategic Engagement (FORGE), a global forum designed to counter market volatility and supply concentration. The State Department has also expanded mineral diplomacy through new bilateral frameworks with countries like Argentina, the Philippines, and the UAE to secure supply chain access [10]. Together, these efforts align agency activities around a multi-pillared strategy to secure the domestic value chain:

- *Diversification of Supply:* Securing resources from diverse sources and feedstocks, including primary mining, byproducts from existing operations, and recycled materials.
- *Material Substitution:* Developing alternative materials that have less supply chain disruption potential and designing less CMM-reliant products and systems.
- *Manufacturing Efficiency:* Improving processing and beneficiation methods to maximize yield and reduce the total volume of raw material required per finished unit.
- *Circular Economy Practices:* Scaling the remanufacture, repair, and recycling of products and materials used in the modern economy to extend their lifetime and reduce the need for raw material extraction.

1.1. Role of NIST

NIST plays an essential and unique role in addressing CMM challenges by supporting the fundamental measurement science, data infrastructure, reference materials (RMs), reference data (RD), and standards necessary to build a secure, efficient, and circular domestic supply chain. By establishing and maintaining objective benchmarks traceable to the International System of Units (SI), NIST reduces the technical and financial risks that often hinder the private sector's adoption of new materials and processes. Specifically, NIST is well-suited to address technical hurdles faced by U.S. industry partners in these four key areas (Figure 2):

1. *Substitution and Alternatives*: NIST has capabilities that integrate high-throughput experiments with computational models. By leveraging these strengths, NIST can develop foundational Integrated Computational Materials Engineering (ICME) approaches needed to design alternative alloys and accelerate the implementation of substitutes that reduce reliance on CMMs while maintaining or improving product performance.
2. *Traceability and Supply Chain Resilience*: NIST is a world leader in developing RMs, reference data, and industry-acknowledged expertise in data exchange mapping and protocol benchmarking. As such, NIST can support targeted measurement methods, instrumentation, and secure data systems (such as blockchain-enabled metrology) necessary to track CMMs from raw extraction through derivative products. This supports the development of a well-mapped supply chain that highlights material provenance and quality.
3. *Identification, Characterization, and Quantification*: As the U.S.'s national metrology laboratory, NIST has deep expertise in analytical chemistry and precision metrology. NIST can develop advanced analytical methods to detect and quantify CMMs within complex matrices, including primary ores and secondary feedstocks like electronic waste (e-waste). This provides industry with the precision instruments needed to evaluate the economic viability of domestic resources.
4. *Separation and Recovery*: NIST has a legacy of thermodynamics and kinetic modeling research. As such, it can strategically advance the metrology behind the innovation and optimization of chemical separation processes. By providing robust metrics for recovery efficiency, NIST can help the private sector scale up technologies for a circular economy, turning waste streams into reliable material inputs.

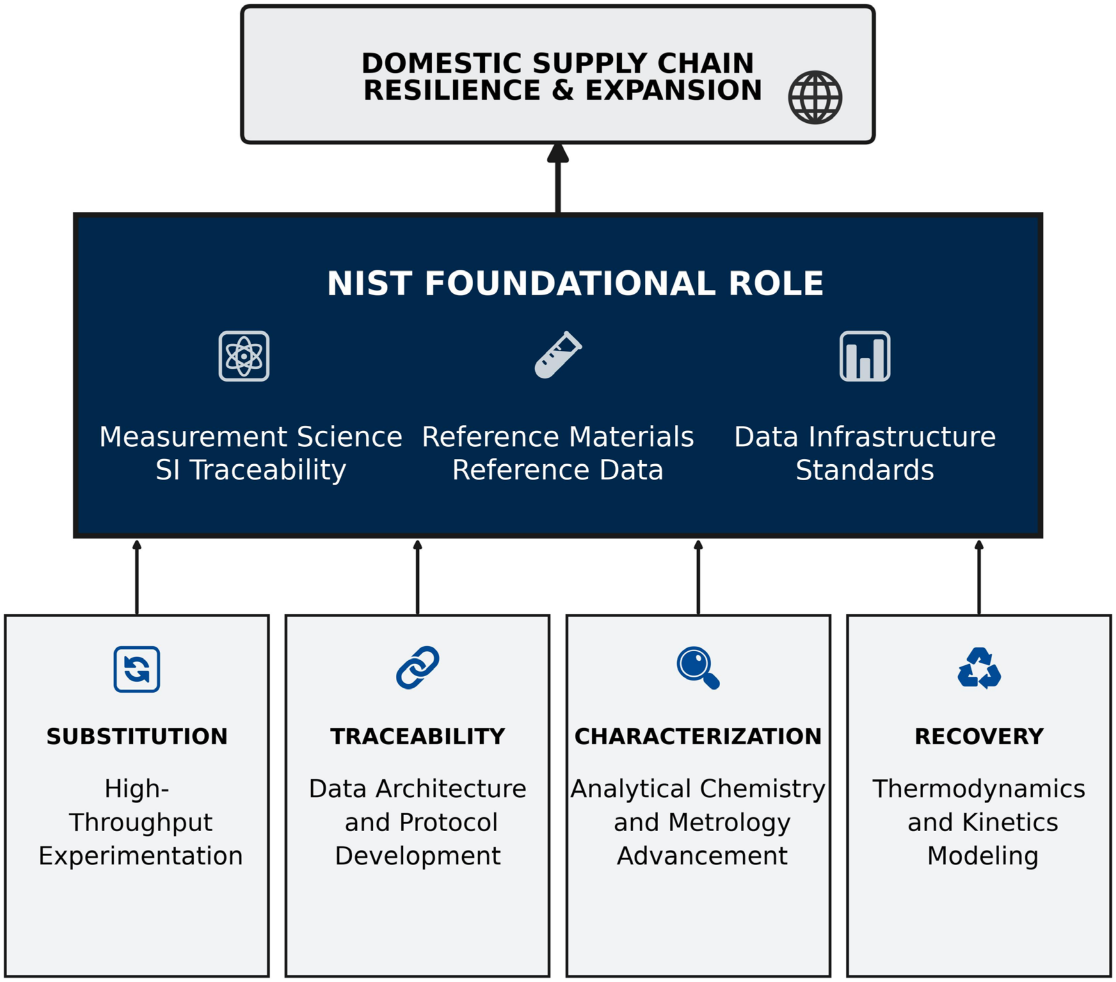

Figure 2: NIST's role in the domestic CMM supply chain. The framework illustrates the flow of NIST's metrological capabilities, including measurement science, reference materials, and data infrastructure supporting the U.S. domestic CMM supply chain.

1.2. NIST internal workshop

An internal workshop held in July 2025 convened NIST researchers to identify existing CMM activities, capabilities, and areas for growth. The workshop brought together experts from across NIST's laboratories to share their research and discuss areas where NIST can make a meaningful impact, both in the short and long term. Workshop presentations focused on the existing measurement science, reference materials, data products, and standards engagements related to CMMs, as well as current expertise and technical capabilities that could be applied to address CMM challenges. In addition, the workshop provided a valuable opportunity for NIST staff to cross-pollinate and identify possible collaborations on new or expanded research that can help address the nation's CMM needs.

The remainder of this report summarizes the outcomes of the workshop, which included presentations, discussions, and a poll focused on NIST's strengths in terms of products and capabilities, as well as its limitations and areas for improvement, and areas of impact in both the short and long term. This report uses many terms and acronyms, detailed in Appendix A. The workshop agenda is provided in Appendix B. The following section highlights NIST's current and potential activities as they relate to CMMs, while Section 3 lists key NIST products that support CMM advancements, including datasets, reference materials, and technical capabilities. Section 4 outlines future directions where NIST could have a meaningful impact.

2. CMM Activities at NIST

NIST has a range of research activities and capabilities that can be applied to address the challenges associated with CMMs. This section provides a detailed overview of both the current research efforts and the existing capabilities that could be leveraged to support CMM-related research and development.

2.1. Substitution and Alternatives

NIST is advancing measurement science and providing data that can support the development and assessment of alternative materials and processes aimed at reducing reliance on CMMs (Figure 3).

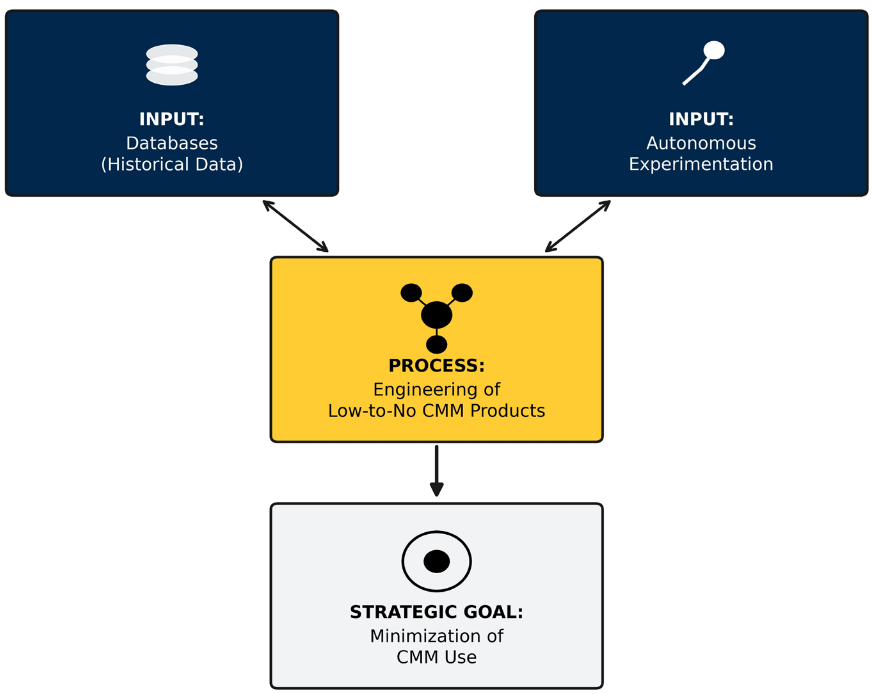

Figure 3: A NIST accelerated material metrology framework: leveraging data-driven inputs and autonomous labs to engineer next-generation materials with low-to-no CMM content.

2.1.1. Databases

NIST maintains several databases that can be leveraged to explore CMM element substitutions, alternative material compositions, and resulting structure-property relationships [11]. See section 3.2.1 for a list of relevant NIST data products.

2.1.2. Autonomous Experimentation

Additive manufacturing (AM) combined with high-throughput automated experimentation/detection enables NIST to rapidly map structure-property-processing relationships to reduce CMM needs through alternative materials discovery and process optimization [12] (Figure 4). These autonomous systems enable the exploration of vast composition and process landscapes, utilizing X-ray diffraction and microstructure characterization to define the roles of CMMs in target materials. A key priority of this high-throughput methodology is ensuring that insights gained from bench-scale AM efforts are transferable to traditional manufacturing processes, ensuring industrial utility for newly discovered material alternatives.

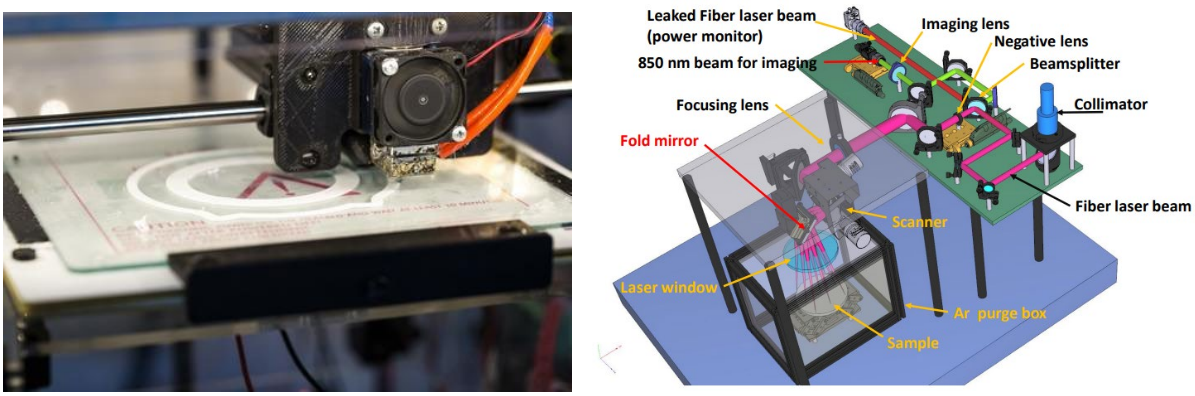

Figure 4: Additive manufacturing constructs objects by layering material, which results in less waste compared to traditional manufacturing methods. NIST has developed pioneering prototype additive manufacturing systems to test state-of-the-art procedures and material designs. Left: Credit Pixabay – lppicture; Right: from [12].

2.1.3. Development of Cobalt-Free Maraging Steels

While cobalt-free maraging steels are commercially available, they may exhibit lower strength after standard processing compared to traditional cobalt-containing alloys. To bridge this performance gap, NIST is evaluating how AM build parameters and heat treatments can be adjusted to optimize the material's internal structure [13], [14]. This research supports the development of processing and post-processing methods that may help cobalt-free maraging steel reach performance parity with legacy materials in demanding industrial applications.

2.1.4. Minimization of CMM Use

Beyond total substitution, NIST has identified opportunities to apply "thrifty use" strategies to reduce the volume of CMMs required for specific functions. In catalysis applications, researchers envision leveraging electrochemical atomic layer deposition to create core-shell architectures, where a thin layer of a PGM is deposited on a non-PGM substrate. This process could enhance catalytic performance while reducing CMM usage and allowing for the exploration of thickness-dependent properties in multilayer films. The process has been demonstrated on various substrates and has potential applications in microelectronics, additive manufacturing, and fuel cells, where it can improve catalyst lifetimes and reduce costs.

2.2. Traceability and Market Dynamics

NIST is advancing measurement methods, modeling, and data systems to understand and track CMMs and their derivative products through supply chains and the economy (Figure 5).

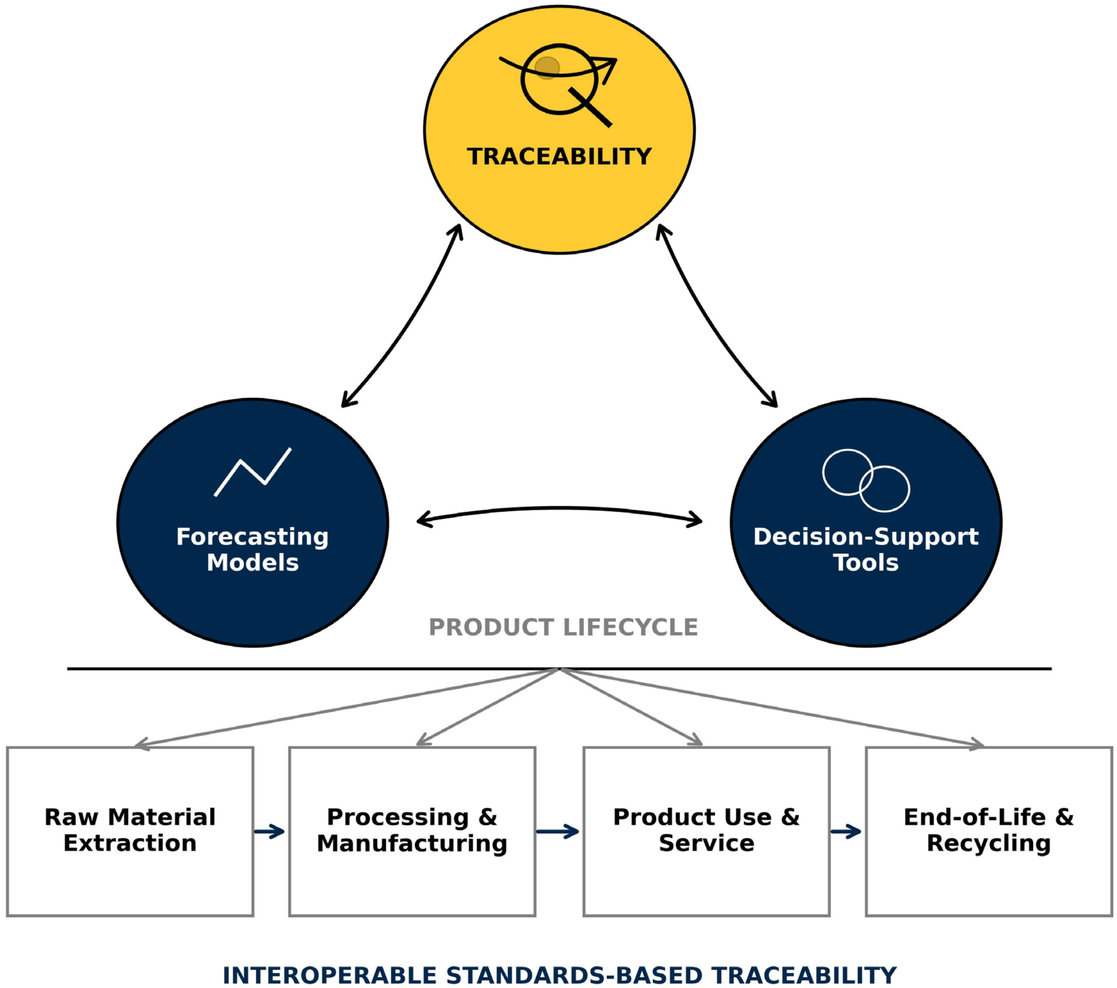

Figure 5: A dynamic integration of forecasting models and decision-support instruments with a centralized data traceability focus. This provides a stakeholder-centered feedback loop that informs and optimizes each stage of the physical product lifecycle, from raw material extraction to end-of-life recycling.

2.2.1. Forecasting Models for CMM Demand

NIST has a focus area on the quantification and traceability of CMMs through a "triple-bottom-line" perspective, emphasizing the strengthening of supply chains via secondary materials recovery [15], [16]. By using material flow analysis (MFA) and diffusion modeling, this work aims to estimate the mass of CMMs currently in circulation and where they can be recovered from end-of-life products. Initial efforts focused on neodymium and dysprosium from sources like hard disk drives, and later included forecasting for other CMMs such as gallium, indium, and cobalt [16], [17], [18]. To address the lack of consistent methodologies for demand forecasting, NIST utilizes diffusion models (e.g., Bass models), to estimate future CMM needs.

2.2.2. Decision-Support for Secondary Materials Markets

NIST is developing computational tools to foster a secondary materials market, focusing on open-loop recovery pathways where materials from one industry, such as solar photovoltaic (PV) waste, become feedstocks for another (such as the automotive or glass industries) [19]. This research employs agent-based modeling to simulate the complex, localized interactions between decommissioning and manufacturing firms, accounting for variables like trust, cost-sharing negotiations, and willingness to adopt secondary materials. By integrating techno-economic analysis and lifecycle assessment metrics, this modeling supports traceability for the value and impact of recovered commodities, such as aluminum, copper, and silicon. This decision-support framework enables stakeholders to analyze the feasibility of secondary-material partnerships across scenarios, including fluctuating recycling costs and supply chain disruptions, ultimately aiming to secure CMM supplies for small and medium-sized enterprises.

2.2.3. Supply Chain Traceability: Manufacturing Meta-Framework

While not explicitly discussed in the workshop, NIST is currently developing a Manufacturing Meta-Framework [20] through the National Cybersecurity Center of Excellence (NCCoE) to explore traceability principles across complex and distributed manufacturing ecosystems. While this framework's primary focus is on discrete manufacturing and software, its foundational concepts offer potential future applications for broader sectors, including CMM supply chains [21]. The framework introduces a conceptual approach for linking and validating summary-level traceability data records for supporting supply chain risk management (SCRM) processes. By establishing mechanisms that allow organizations to independently verify product provenance and pedigree information without requiring suppliers to expose proprietary business information, this framework provides a foundation that could eventually assist stakeholders in assessing supply chain integrity and managing supply chain risk across the wider manufacturing sectors.

2.3. Identification, Characterization, and Quantification

NIST is leveraging a multi-scale metrology portfolio to identify, characterize, and quantify CMMs across their entire lifecycle; from geological exploration and primary extraction to the analysis of complex, heterogeneous secondary waste streams (Figure 6).

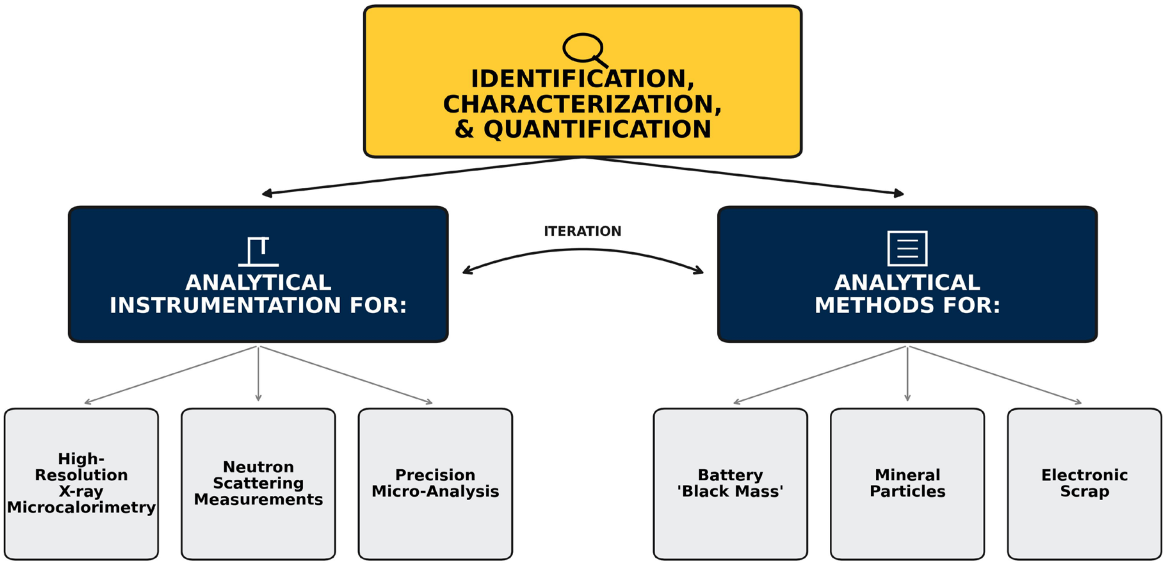

Figure 6: A strategic coordination between advanced analytical instrumentation and validated methods. Feedback between these two efforts ensures the precise identification, characterization, and quantification of CMMs within complex waste streams, such as battery "black mass" and electronic scrap.

2.3.1. Analytical Instrumentation

NIST maintains a suite of analytical capabilities, including neutron-based analytical methods (neutron activation analysis (NAA), prompt gamma activation analysis (PGAA), and neutron depth profiling (NDP)), inductively coupled plasma mass spectrometry, optical emission spectroscopy (ICP -MS, - OES), X-ray fluorescence spectroscopy (XRF), and a host of industry utilized methods (gravimetry, coulometry, titrimetry) that measure elemental content, speciation, and isotopic signatures.

Additionally, hyperspectral imaging standards can facilitate geographic and geological exploration of CMM stockpiles by providing a spatially scalable remote sensing modality – ranging from microscopic to satellite scales – that utilizes spectral signatures for the rapid identification and quantification of minerals [22], [23], [24].

2.3.2. High-Resolution X-ray Microcalorimetry

MML's developments in X-ray microcalorimetry analysis offer opportunities to characterize elemental composition and distribution in microstructures, providing significant improvements in energy resolution over conventional energy-dispersive X-ray spectroscopy. A microcalorimeter X-ray detector, in conjunction with a scanning electron microscope (SEM) (shown in Figure 7) has been demonstrated to be a practical instrument for quantitative analysis. The sharper energy resolution afforded by X-ray microcalorimetry provides more precise differentiation of elements with overlapping X-ray emission lines (such as REEs) and could enable detection capabilities of minor components in complex matrices [25], [26], [27].

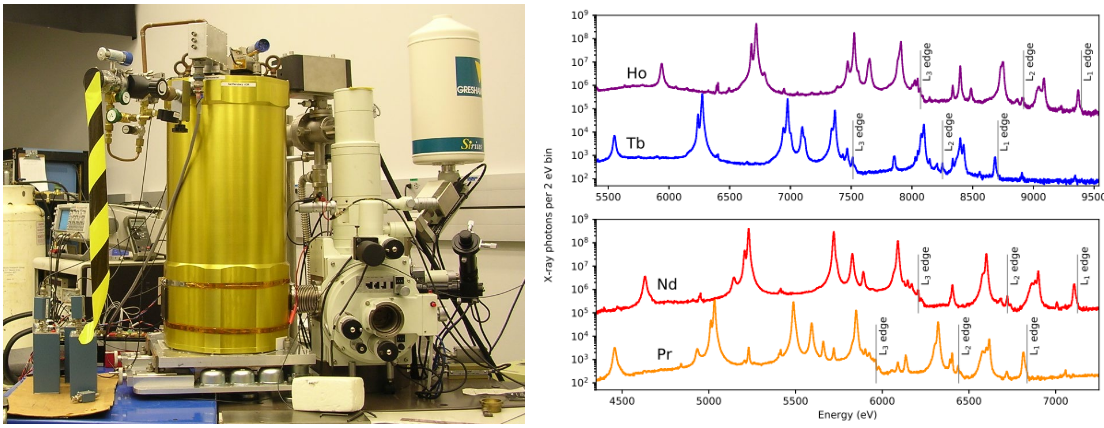

Figure 7: (Left) Microcalorimeter X-ray detector connected to a scanning electron microscope. (Right) Emission spectra of four samples (Ho, Nd, Pr, and Tb are CMMs) collected using this instrument. The Ho and Nd spectra are scaled up by a factor of 1000 for clarity. Credit: Left, NIST; Right, from [25].

2.3.3. Neutron Scattering and Structural Characterization

The NIST Center for Neutron Research (NCNR) offers unique, non-destructive capabilities that complement X-ray techniques by providing high depth penetration even through X-ray-blocking containers, enabling "in operando" measurements of materials during active processes. Neutrons are uniquely sensitive to magnetic moments and can distinguish between neighboring elements on the periodic table, making them essential for the structural elucidation of magnetic materials, energy storage systems, and advanced alloys [28], [29], [30]. While no CMM-specific activities are currently underway, the long-standing community partnerships established through user-facility engagements and existing consortia (e.g., nMat, previously nSoft) provide a foundation for future research activities in structural elucidation of CMM-reliant materials.

2.3.4. Characterization and Metrology for Battery "Black Mass"

NIST is focusing on the characterization of battery "black mass," shredded or size-reduced end-of-life lithium-ion batteries, and battery manufacturing scrap [31]. Black mass often contains significant concentrations of CMMs but presents major measurement challenges due to its extreme physical and chemical heterogeneity.

To bridge the gap in domestic processing capacity, NIST is investigating benchmarking measurement protocols using ICP-OES, PGAA, and NDP to accurately quantify "payable" elements, such as cobalt, nickel, and lithium, while identifying detrimental impurities, including fluorine, phosphorus, and chlorine. These instruments have been previously used to measure one or more of the listed elements [32], [33], [34], [35], [36]. These efforts include benchmarking chemical variability across different lithium battery chemistries and contributing to international standards through ISO/TC 333 (Lithium) to ensure domestic recyclers can meet global trade and purity requirements [37].

2.3.5. Precision Micro-Analysis of Mineral Particles

NIST has identified a potential opportunity to apply "NIST-on-a-chip" or “Lab on a chip” technology [38], [39] to the characterization of critical mineral particles present in complex matrices such as coal fly ash. By leveraging cavity optomechanics, it may be possible to measure the mass and density of microscopic particles with high precision [38], [40] (Figure 8). This capability could be used to identify and quantify REE-rich particles within coal fly ash, providing the fundamental data necessary to evaluate the feasibility and economic viability of extracting CMMs from these vast, non-traditional feedstocks.

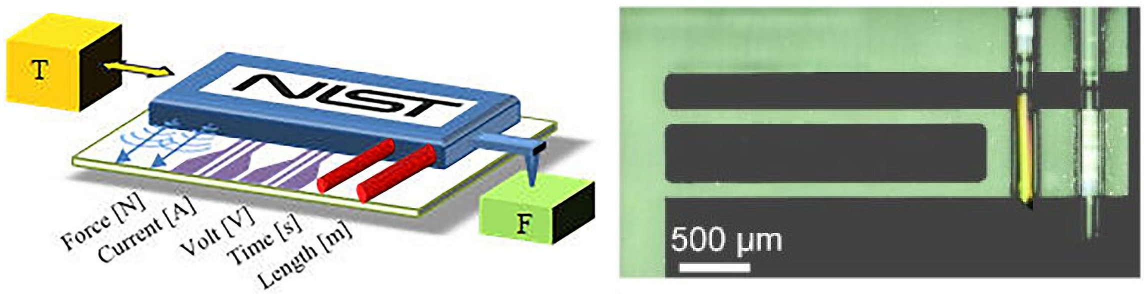

Figure 8: NIST-on-a-chip platform (general theory diagram, left) can use cavity optomechanics (right) for high-precision mass and density analysis of coal fly ash. These data enable the identification of REE-rich particles to evaluate the economic feasibility of CMM extraction. Credit: Left, NIST; Right [36].

2.3.6. Characterization and Benchmarking of Electronic Scrap

NIST is working to characterize electronic scrap, or e-scrap (also referred to as e-waste), which varies significantly in elemental composition depending on the type of waste electronic component (e.g., batteries, processing scrap, or consumer electronics) using a variety of analytical instruments including PGAA, ICP-OES, SEM, TGA-MS, and XRF [41]. Because e-scrap varies significantly in elemental composition depending on the type of waste (e.g., consumer electronics), any proposed analysis framework should be established and benchmarked using multiple true-industry samples. Potential roles for NIST include establishing industry-ready metrologies compatible with existing processing lines, strengthening information flows and decision-making tools in material processing, developing standard analysis methods, and exploring representative e-scrap reference materials.

2.4. Separation and Recovery

NIST is establishing the measurement science and thermodynamic data necessary to optimize the extraction of CMMs from complex waste streams. Current efforts focus on providing the technical foundation for industrial-scale separation processes that are currently hindered by composition heterogeneity and high processing costs (Figure 9).

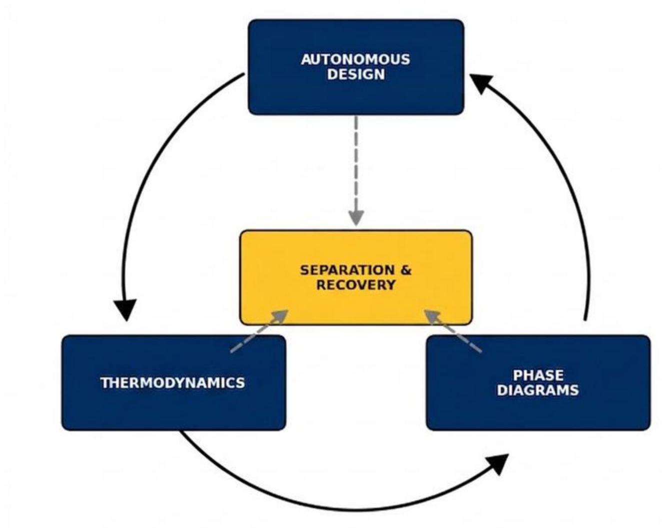

Figure 9: An iterative cycle integrating autonomous design with foundational thermodynamic and phase equilibria modeling to optimize mineral recovery.

2.4.1. Thermodynamic Quantification for Microelectronic Waste

NIST is addressing supply chain vulnerabilities in the semiconductor industry by developing a metrological foundation for the separation and recovery of key CMMs, specifically gallium, indium, and antimony, from microelectronic waste. The effort employs a multi-faceted approach, utilizing pyrometallurgical (vacuum distillation), membrane/sorbent (solution separation), and electrochemical methods to characterize material behavior across various recovery pathways. By generating actionable data on thermodynamic and kinetic parameters during separation, NIST is providing a technical foundation to support CMM recovery.

2.4.2. Impurity-Tolerant Alloy Design

To support the circularity of structural metals, NIST is investigating the design of alloys that can tolerate higher levels of contaminants found in recycled scrap. A primary example is the development of steel alloys capable of accommodating increased copper (Cu) concentrations without sacrificing mechanical or corrosion performance. By utilizing an ICME approach that combines physics-based and statistical models, NIST seeks to create a robust framework that enables the up-cycling of scrap material into high-demand applications, reducing the need for high-quality primary metal that has both high embodied energy and cost. A key objective of this work is to map impurity content to alloy properties, which would provide the technical basis for alloy standards development. Through such standards, compositional windows could be expanded to accommodate higher levels of scrap during the production of metal alloys.

2.4.3. Sustainable Metals Processing

NIST is building an integrated, high-throughput workflow for the design, fabrication, and testing of metallic alloys that reduces reliance on primary CMM sources. This effort leverages computational thermodynamics to explore novel alloy compositions that can be used to replace CMM alloying elements in existing metallic materials or to develop impurity-tolerant alloys. Once target compositions are identified, they are synthesized using application-relevant processing routes. For example, the use of a small-scale ultrasonic atomizer, which accepts irregular recycled feedstock and converts it into high-quality metal powders suitable for AM.

These materials are used in the NIST System for AM Alloy Development (SAMAD) to enable precise control over material composition and accelerate the development of sustainable alloy systems. Following fabrication, high-throughput characterization and property testing methods are applied to evaluate the predicted compositions. Combined, this integrated strategy offers a technical baseline to overcome hurdles in establishing a sustainable metal processing framework, as detailed in a recent NIST workshop report [42].

3. NIST's Technical Capabilities

This section of the report outlines the core technical infrastructure and capabilities NIST can leverage to address the complex challenges of CMMs, as discussed in the workshop.

3.1. Measurement, Characterization, and Analysis

NIST maintains a comprehensive suite of advanced analytical instruments and deep expertise in measurement science. Table 1 summarizes the existing equipment and methods identified during the workshop as essential for identifying, quantifying, and validating CMMs across diverse feedstocks – from raw ores to complex electronic scrap.

Table 1: NIST's CMM-related Measurement and Analysis Capabilities (see Appendix A for acronyms and abbreviations)

Category	Equipment /Method	Function and CMM Application
Advanced Imaging	*TIR*	**Matrix analysis**: Maps silicates and carbonates. Essential for analyzing waste rock (gangue) in critical mineral ores.
	VNIR/SWIR	**Mineral ID:** Uses reflectance to identify oxides; scalable from microscopic to satellite scales.
Atomic & Optical Spectroscopy	*ICP-MS*	**Ultra-trace analysis**: Isotopic analysis (parts per trillion). High sensitivity for REEs in high-purity or diluted samples.
	ICP-OES	**Bulk analysis**: Quantitative analysis of major/minor components. Better suited for complex samples like ores and e-waste.
	XRF	**Field screening**: Non-destructive chemical identification. Handheld versions allow for rapid field screening of ore grade.
Electrochemistry	*High-Precision Potentiostat*	**Reaction kinetics**: Precise measurement of metal purity and reaction rates; essential for validating refining processes.
	Spectro-electrochemical Cells	**Real-time monitoring**: Integrates a potentiostat with Raman/IR to map deposition potential against real-time chemical state.

Microscopy & Surface Science	*SEM-EDS*	**Chemical mapping**: High-resolution imaging and local mapping (>100 nm) to identify mineral grains in waste.
	SIMS	**Thin film analysis**: Useful for analyzing trace elements and isotopic variations in critical mineral grains or thin-film energy materials.
	X-ray Microcalorimetry	**Spectral resolution**: High-resolution X-ray detection to resolve overlapping spectral lines of familial elements like REEs.
Nuclear & Neutron Analysis	*INAA*	**Bulk elements and trace impurities**: Highly sensitive multi-elemental analysis (ppb). Excellent for CMM alloys.
	NDP	**"Light" element profiling**: Nominally non-destructive, near-surface neutron method especially sensitive to Li, He, B, N, and Cl.
	PGAA	**Bulk elements**: Non-destructive analysis of elements like H, B, and Li and other elements that may be difficult to measure with X-rays.
	RNAA	**Complex matrices**: Specialized neutron analysis using post-irradiation chemical separation for lowest detection limits.
Physical & Particle Metrology	*Cavity Optomechanics*	**Particle metrology**: Uses laser photon pressure to measure mass and density of individual microscopic particles.
Thermal & Recovery Metrology	*ITC*	**Binding thermodynamics**: Measures heat of chemical binding to determine affinity and stoichiometry for recovery agents.
	TGA-GC-MS	**Distillation kinetics**: Measures mass loss and gas composition to find activation energies for selective vacuum distillation.

3.2. Data, Modeling, and Computation

NIST maintains an extensive materials data infrastructure and deep expertise in advanced computational methods, serving as the digital backbone for CMM research and supply chain resilience. This ecosystem integrates high-fidelity databases, predictive modeling, and economic analysis tools to accelerate material discovery and mitigate supply chain vulnerabilities.

3.2.1. Materials Data Infrastructure

NIST hosts an extensive suite of external-facing databases and registries, including efforts under the Materials Genome Initiative (MGI), that can be leveraged to address CMM challenges. These resources provide the structural and thermophysical data necessary to inform separation, substitution, and material recovery. Table 2 highlights the specific NIST materials databases applicable to CMMs research.

Table 2: External-Facing Digital Assets for CMM Materials Research

Database / Registry (Hyperlinked)	Asset Type	Description and CMM Application
CALPHAD Database Repositories	*Thermodynamic/Kinetic*	Infrastructure of files used to predict multi-component behavior, accelerating novel alloy development and processing
JARVIS (ML, FF, DFT)	*Computational/AI*	Uses Density Functional Theory (DFT) and machine learning to drive data-driven critical materials design
Materials Data Curation System	*Software Platform*	Open-source platform used to manage, standardize, and share experimental and computational CMM data via XML schemas
NIST Materials Resource Registry	*Digital Directory*	A high-level search tool to discover and navigate NIST's diverse materials data assets and relevant third-party repositories
Thermodynamics Research Center: NIST Alloy Data	*Experimental Property Data*	Web application containing curated thermophysical property datasets for metal systems; critical for optimizing refining and casting
NIST Inorganic Crystal Structure Database	*Structural Data*	Detailed crystallographic data on inorganic compounds; essential for identifying mineral phases via diffraction techniques
Materials Data Repository	*Open Repository*	A centralized hub for hosting, archiving, and sharing FAIR (Findable, Accessible, Interoperable, and Reusable) materials data
ACerS-NIST Phase Equilibria Diagrams Database	*Phase Equilibria*	Standard reference database produced with the American Ceramic Society; used to design chemical extraction and liquid-solid separation processes

While these repositories contain vast amounts of valuable materials property data, much of the information remains trapped in legacy formats or reference publications that lack machine readability and consistent metadata. Fully realizing the potential of these resources requires modernizing the infrastructure by developing advanced methods to accurately import and digitize legacy records. By improving metadata consistency and machine accessibility, NIST could integrate artificial intelligence and machine learning (AI-ML) algorithms into data curation and analysis, ensuring its foundational repositories are optimized for modern digital workflows and autonomous discovery platforms.

3.2.2. Computational Material Science and AI-ML

NIST bridges the gap between computation and experiment, transforming static data into predictive tools and developing the supportive methodologies required for accelerated material discovery.

- *High-Throughput Modeling and Virtual Screening:* NIST possesses the computational infrastructure to perform high-throughput "virtual screening" of thousands of material compositions before physical synthesis. By leveraging first-principles methods, such as Density Functional Theory, and surrogate models trained on JARVIS datasets, NIST can predict fundamental properties, such as formation energy and mechanical stability, to identify "drop-in" substitutes for CMMs.
- *Autonomous Discovery Platforms:* NIST has autonomous laboratory capabilities that utilize active learning loops and AI-based surrogate models to orchestrate robotic synthesis and characterization. This enables researchers to navigate vast compositional spaces, such as high-entropy alloys, while requiring 10–100x fewer physical experiments.
- *Computational Calibration via Dynamic Characterization:* To anchor its predictive models to real-world experimental results, NIST has utilized high-speed synchrotron X-ray diffraction to capture millisecond-scale phase changes during non-equilibrium processing. This high-fidelity experimental data serves as a calibration source for ICME and CALPHAD models, enabling digital twin-based performance predictions for novel, CMM-lean alloys.

3.2.3. Economic and Circularity Modeling

NIST provides foundational data and reference models required for comparative analysis, enabling researchers and industry stakeholders to objectively evaluate competing technology pathways. By supporting the development of standardized, open-source frameworks, NIST ensures that assessments of environmental and economic performance are transparent, interoperable, and reproducible.

- *Life Cycle Assessment (LCA):* NIST develops reference LCA models and templates to improve the consistency of results. These tools enable comparative analysis of environmental trade-offs across different production and recycling methods.
- *Material Flow Analysis (MFA):* NIST provides systematic frameworks to quantify material stocks and flows across global and domestic boundaries. These models help stakeholders identify opportunities for recovered CMM feedstocks.
- *Demand Forecasting:* Using models like the Bass Diffusion Model, NIST produces datasets to project technology adoption and subsequent material needs. These projections allow for "what-if" scenario planning to compare how emerging technologies will impact long-term material availability.

3.3. Standards and Reference Materials

A recurring theme of the workshop was the necessity of a harmonized global standards infrastructure to reduce market volatility and technical barriers. NIST’s contributions in this area span the development of physical artifacts for calibration and leadership in international bodies to ensure U.S. interests are represented in the global CMM market.

3.3.1. Standard Reference Materials (SRMs)

NIST produces and maintains a portfolio of reference materials designed to ensure the accuracy and comparability of measurement results across the global supply chain. This portfolio consists of high-purity reference materials, such as pure elements and chemical compounds used for precise calibration, as well as matrix reference materials that contain elements within complex, real-world samples to enable measurement validation and quality control.

A cornerstone of the high-purity offerings is the SRM 3100 series (Spectrometric Single Element Standard Solutions), widely regarded as the international benchmark given that no other national metrology institute in the world provides similar metrological instruments on a comparable scale. This series offers a primary traceability link to the SI for 66 individual elements, effectively supporting many of the listed CMMs, as illustrated in Figure 10. The table in Appendix C shows the alignment between the DOE/USGS CMMs lists and the NIST SRM 3100 Series.

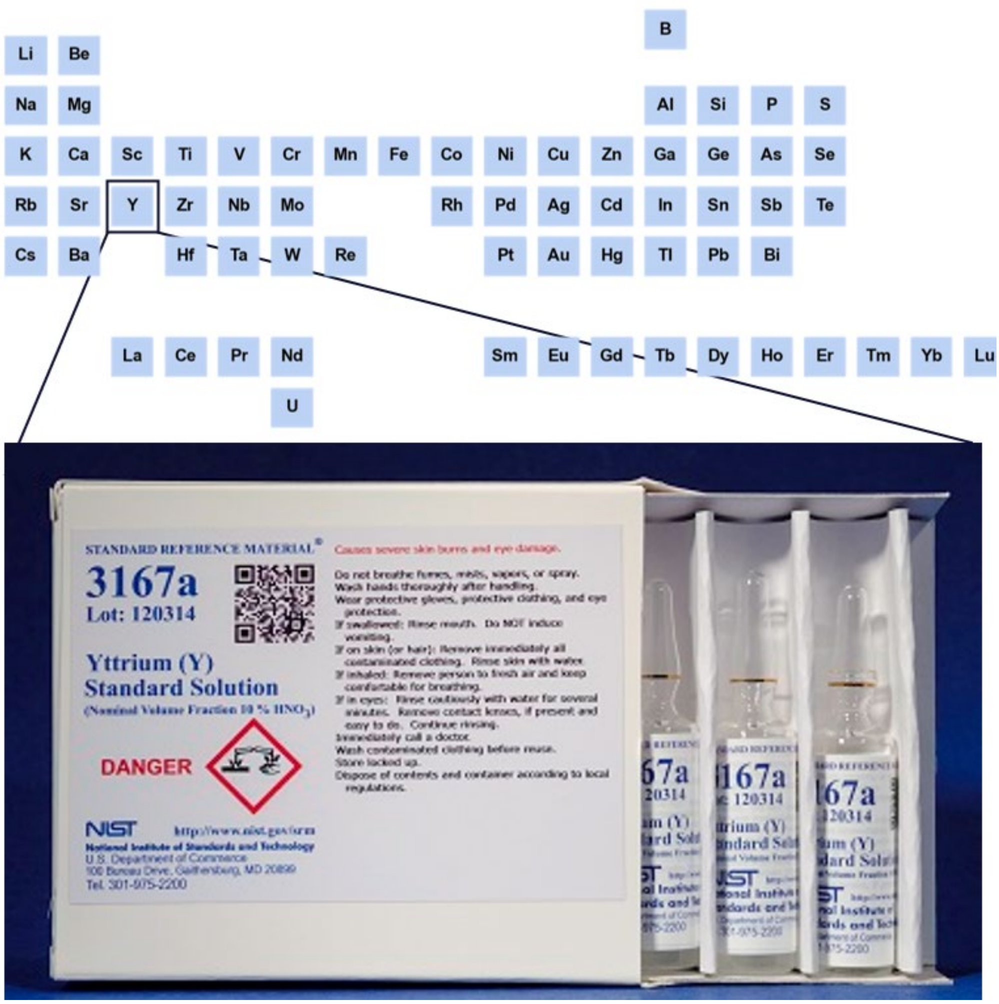

Figure 10: (Top) The single-element standards included in the NIST SRM 3100 series encompass a range of CMMs indicated by the blue elements. (Bottom) NIST SRM 3167a, Yttrium (Y) standard solution, part of the 3100 series, is used to quantify CMMs across various materials, serving applications from basic research to quality assurance and quality control in industrial production. Credit: NIST.

NIST also produces and maintains reference materials that contain elements within a complex sample matrix, which are used for measurement validation and quality control. The current portfolio includes rocks and minerals (12 SRMs), ores (23 SRMs), soils and sediments (13 SRMs), non-ferrous metals (90+ SRMs, including Aluminum, Cobalt, Copper, Lithium, Nickel, Titanium, and Zirconium metals).

3.3.2. Documentary Standards

NIST actively participates in documentary standards committees to support the technical underpinnings of supply chain resilience, ensuring that methods for characterizing, recycling, and certifying CMMs are grounded in accurate, consensus-driven measurement science. Table 3 shows NIST standards engagements highlighted in the workshop.

Table 3: NIST Standards Organizations and Committees Involvement

Organization	Committee / Standard	NIST Role & Involvement
VAMAS	General & Proposed Steering Committee	As the current chair of VAMAS, NIST coordinates international consensus-building and pre-standards research across global National Metrology Institutes. Efforts include a proposal to establish a new Critical Minerals Steering Committee / Technical Work Area.
ISO	TC 298: Rare Earth	Chairs the U.S. Technical Advisory Group (TAG).
	TC 333: Lithium	Chairs the U.S. Technical Advisory Group (TAG).
	TC 345: Materials for Specialty Technologies	Chairs the U.S. Technical Advisory Group (TAG).
	TC 82/TC 7: Sustainable Mining and Closure	Participates as a member of the U.S. Technical Advisory Group (TAG).
	ISO/ASTM 52911-3: Additive Manufacturing	Participate in the development of joint international manufacturing and materials testing guidelines.
ASTM International	ASTM F3592: Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Re-use and Sampling Strategies	Collaborated with industry partners to draft and validate guidelines governing powder feedstock reuse and sampling in metal additive manufacturing.
	Advanced Manufacturing	Maintains active leadership and technical involvement in the ASTM International Conference on Advanced Manufacturing (ICAM).
IEEE	P4001: Characterization and Calibration of Hyperspectral	Contributes core metrology expertise to standardize calibration metrics for

Organization	Committee / Standard	NIST Role & Involvement
	Imaging Devices Working Group	advanced hyperspectral imaging devices used in mineral mapping.
	P4005: Standards and protocols for soil spectroscopy	Collaborates on the baseline development of standardized spectroscopic protocols for environmental and geologic soil tracking.
SAE International	Battery Global Traceability Standards Committee	Participates in crafting global data traceability frameworks, ensuring standardization across mineral provenance tracking, battery performance logging, and lifecycle interoperability.
	Battery Standards Recycling Committee	Supports the establishment of standardized industry nomenclature, chemical identification schemas, and safe disassembly methodologies for end-of-life battery recycling.

3.3.3. Proposed and Emerging Standards for CMMs

The workshop identified a critical need for new physical and documentary standards to keep pace with rapid technological shifts and the growth of secondary material markets. While SRMs provide the physical basis for measurement, documentary standards may establish the "rules of the road" for domestic commerce, international trade, regulation, and industrial adoption. Specific emphasis was placed on:

- *Supply Chain Traceability:* NIST is actively involved in the development of international documentary standards that ensure the traceability of CMMs through the supply chain. This includes NIST's role as chair of the U.S. Technical Advisory Groups for ISO/TC 298 (Rare Earth) and ISO/TC 333 (Lithium). NIST is also participating in the development of SAE J3327 – Electric Vehicle (EV) Battery Traceability Record through the Battery Global Traceability Standards Committee to standardize CMM data collection and interoperability across the supply chain, enabling industry to comply with emerging traceability requirements.
- *Black Mass Metrology:* Workshop discussions highlighted the current industrial needs for battery black mass metrology. NIST has completed stakeholder engagement activities to learn more about community needs regarding "payable" element grades (e.g., lithium, cobalt, nickel) and impurity thresholds (e.g., fluorine, chlorine) to facilitate domestic commerce and global trade. NIST is now working with standard development organizations to facilitate the accurate measurement of these elements through analytical methods development and verification.
- *Secondary Market Metrics:* Speakers highlighted the need for standards to classify impurity content in scrap, allowing manufacturers to confidently "up-cycle" materials with known levels of contaminants, such as copper in recycled steel.

- *Hyperspectral Calibration and Detection:* Standards-based solutions are necessary to reduce detection uncertainties in mineral mapping across varying scales. Key requirements include SI-traceable spectrometer calibration, protocols for laser-based hyperspectral microscopy to differentiate materials in complex mixtures, and the development of optical reflectance reference targets for pure samples and variable backgrounds. Additionally, advanced field-deployable references are needed to provide "ground truth" at recovery sites.
- *Expansion and Recertification of SRMs:* NIST has identified the need for new, priority high-purity SRMs to fill gaps in the periodic table (Figure 10) and is exploring the reclassification of existing matrix SRMs to certify trace elements, including REEs.

3.4. Advanced Manufacturing & Processing

NIST's manufacturing testbeds and materials processing expertise provide a high-fidelity environment for evaluating material performance under industrial conditions. These capabilities can be utilized to optimize the use of CMMs, facilitate the adoption of recycled feedstocks, and establish the technical basis for industrial-scale recovery.

- *Additive Manufacturing (AM) Systems:* NIST maintains advanced platforms such as the System for AM Alloy Development (SAMAD), which is capable of site-specific, multi-material deposition. This allows for the precise placement of CMMs only where needed, significantly reducing material requirements.
- *Secondary AM feedstock Preparation:* NIST possesses small-scale ultrasonic atomization capabilities that can convert irregular or recycled feedstock, such as scrap metal, into spherical powders capable of additive manufacturing. This capability enables the rapid evaluation of secondary material feedstocks as viable manufacturing inputs.
- *Advanced Deposition and Catalysis:* NIST can utilize electrochemical atomic layer deposition to achieve monolayer-level control over material placement. This is particularly relevant for the "thrifty" use of PGMs, where core-shell architectures can be engineered to enhance catalytic performance while using orders of magnitude less precious metal.

4. Proposed Future Directions for NIST CMM Strategy

Based on July 2025 workshop outcomes and strategic institutional goals, NIST is poised to deepen its fundamental measurement science, data infrastructure, and metrological applications to reduce the nation's dependence on CMMs. The following future research directions are designed to help the U.S. industrial base transition toward a resilient, circular supply chain where high-fidelity data and validated benchmarks empower manufacturers to innovate, substitute, and recover materials with precision and confidence.

4.1. Modernize, Integrate, and Expand CMM Data Infrastructure

Manufacturers and process engineers need high-fidelity, SI-traceable materials and associated data sets to develop new processes for CMM reduction and recycling. NIST can provide a modern, complex data library focusing on computationally intensive thermodynamics, structure, and composition of CMM-containing materials.

- *Near-Term (1-3 Years):* Launch a pilot program to digitize materials data into machine-readable formats with standardized application programming interface (API) compatibility for immediate integration into ICME and AI/ML workflows.
- *Long-Term (5-10 Years):* Advance toward an integrated digital twin infrastructure for CMMs, linking NIST's foundational datasets with real-time experimental data from autonomous labs to support rapid virtual qualification.

4.2. Support the Development of Field-Deployable Rapid Analytical Instruments

Decision-makers require cost-effective, real-time analytical instruments to characterize and qualify material inputs, particularly for the highly complex, low-volume streams characteristic of CMM extraction and recycling. NIST can provide the metrological foundation for the development of field-deployable, rapid, and high-precision analytical tools designed for real-time compositional measurement across a range of materials.

- *Near-Term (1-3 Years):* Develop next-generation laser-driven hyperspectral reference instruments and "NIST-on-a-chip" mass/density sensors to serve as "field truth" for industry stakeholders.
- *Long-Term (5-10 Years):* Partner with companies to integrate these hyperspectral and optomechanical sensors across the range of extraction, processing, and recovery stages to ensure reliability at industrial scales.

4.3. Accelerate Substitution and Alternatives Discovery

Data gaps persist across the CMM materials landscape, stalling the transition to CMM-free alternatives. NIST can utilize autonomous experimentation systems to rapidly generate high-fidelity, high-throughput data that populates the gaps in current material libraries, enabling the predictive design and optimization of CMM-reliant material systems.

- *Near-Term (1-3 Years):* Utilize autonomous experimentation (like the SAMAD platform) to generate high-throughput data that fills gaps in current libraries, focusing on the characterization of recycled powders and CMM-lean alloys.
- *Long-Term (5-10 Years):* Leverage autonomous discovery to map vast compositional spaces, such as high-entropy alloys. This will enable the identification of "drop-in" substitutes that eliminate the need for minerals like cobalt or chromium in high-stress applications.

4.4. Establish an Industry Consortium for CMM Recovery

A lack of quality assurance and performance benchmarks prevents manufacturers from integrating recycled CMM content into high-value applications. NIST can convene a stakeholder consortium of recyclers and manufacturers to drive pre-competitive research aimed at establishing a cross-cutting quality assurance program.

- *Near-Term (1-3 Years):* Focus on identifying pre-competitive research needs by convening a stakeholder consortium (including recyclers and OEMs) to harmonize purity tolerances and characterization methods for secondary materials. This will prioritize establishing the technical foundation necessary to provide the certainty required for the wide-scale industrial adoption of recycled content.
- *Long-Term (5-10 Years):* Advance the identified research needs and transition the outcomes to industry through a Shared Technology Transfer Pilot to bridge the gap between lab-scale measurement science and commercial implementation. Continue supporting international documentary standards (e.g., ISO/TC 298, TC 333, and TC 345) to ensure US-based recovery processes remain globally competitive and reliable for high-end manufacturing.

4.5. Develop and (re)Certify Standard Reference Materials (SRMs)

Physical artifacts serve as essential benchmarks for industrial measurements, yet specialized SRMs do not exist for many complex CMM-rich materials. NIST can recertify existing SRMs, as well as fast-track the development of a new, industry-relevant suite of SRMs to ensure measurement accuracy and traceability across the CMM value chain.

- *Near-Term (1-3 Years):* Identify and prioritize the most urgent needs for new CMM reference materials, specifically targeting REE magnets, electronics, and batteries. Simultaneously, review and recertify existing matrix SRMs (such as ores, alloys, and sediments) to validate and quantify their content for CMMs that were not previously characterized or certified.
- *Long-Term (5-10 Years):* Expand the SRM portfolio to include complex matrix-matched materials for primary and secondary CMM feedstocks.

4.6. Institutional Alignment and Laboratory Synergy

The successful execution of these research directions would require a multi-disciplinary “One NIST” approach that leverages the specialized expertise across NIST’s laboratories and divisions. By coordinating measurement science, structural characterization, and systems engineering, NIST can ensure that fundamental research is effectively translated into industrial applications. Figure 11 summarizes the primary laboratory and division leads for each of the identified future research directions.

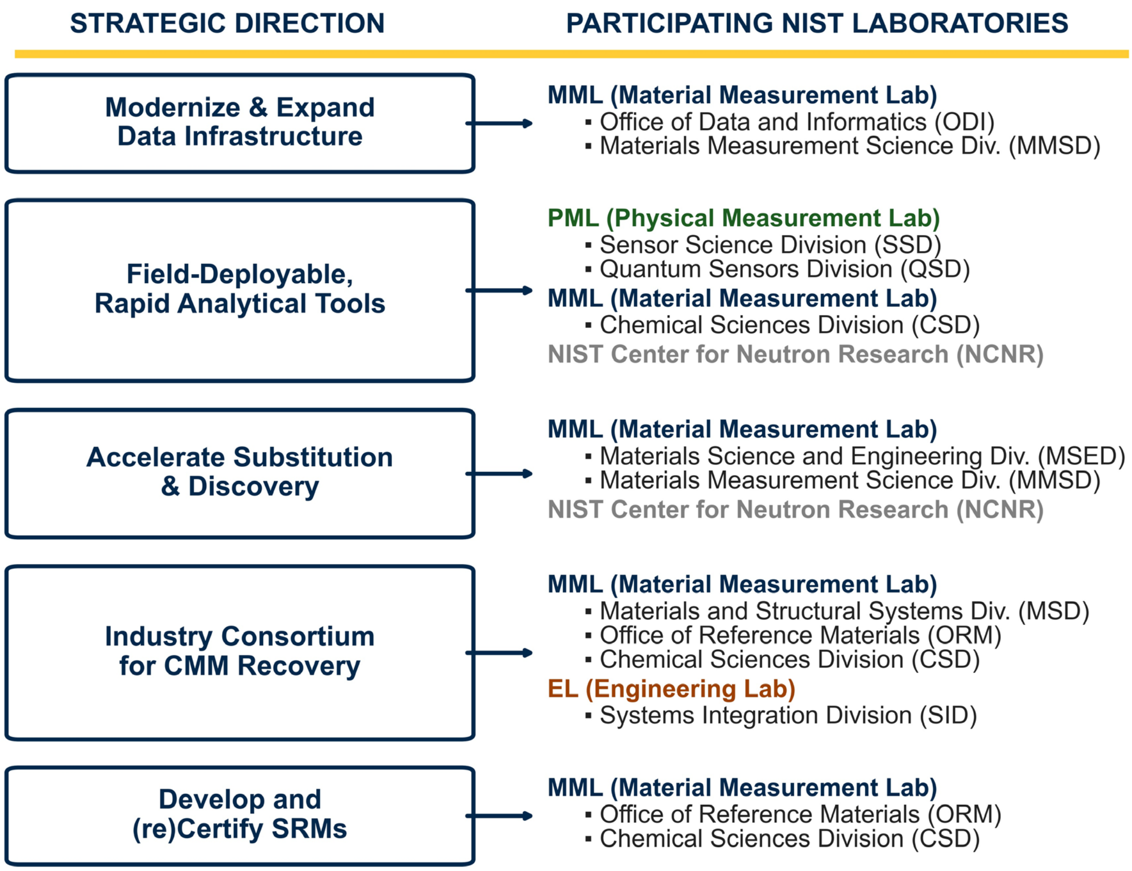

Figure 11: Proposed CMM metrology and research strategy map for NIST laboratories.

References

[1] H. [D-T.-28 Rep. Cuellar, "H.R.133 - 116th Congress (2019-2020): Consolidated Appropriations Act, 2021." Accessed: Feb. 17, 2026. [Online]. Available: https://www.congress.gov/bill/116th-congress/house-bill/133
[2] N. T. Nassar *et al.*, "Methodology and technical input for the 2025 U.S. List of Critical Minerals—Assessing the potential effects of mineral commodity supply chain disruptions on the U.S. economy," U.S. Geological Survey, 2025–1047, 2025. doi: 10.3133/ofr20251047.
[3] "About the 2025 List of Critical Minerals | U.S. Geological Survey." Accessed: Feb. 17, 2026. [Online]. Available: https://www.usgs.gov/programs/mineral-resources-program/science/about-2025-list-critical-minerals
[4] "Notice of Final Determination on 2023 DOE Critical Materials List".
[5] P. [R-M.-8 Rep. Stauber, "H.R.4090 - 119th Congress (2025-2026): Critical Mineral Dominance Act." Accessed: Feb. 13, 2026. [Online]. Available: https://www.congress.gov/bill/119th-congress/house-bill/4090
[6] E. Orders, "Unleashing American Energy," The White House. Accessed: Feb. 13, 2026. [Online]. Available: https://www.whitehouse.gov/presidential-actions/2025/01/unleashing-american-energy/
[7] E. Orders, "Immediate Measures to Increase American Mineral Production," The White House. Accessed: Feb. 13, 2026. [Online]. Available: https://www.whitehouse.gov/presidential-actions/2025/03/immediate-measures-to-increase-american-mineral-production/
[8] E. Orders, "Ensuring National Security and Economic Resilience Through Section 232 Actions on Processed Critical Minerals and Derivative Products," The White House. Accessed: Feb. 13, 2026. [Online]. Available: https://www.whitehouse.gov/presidential-actions/2025/04/ensuring-national-security-and-economic-resilience-through-section-232-actions-on-processed-critical-minerals-and-derivative-products/
[9] "Introducing Project Vault, a critical mineral stockpile for American businesses," The White House. Accessed: Apr. 02, 2026. [Online]. Available: https://www.whitehouse.gov/videos/introducing-project-vault-a-critical-mineral-stockpile-for-american-businesses
[10] "2026 Critical Minerals Ministerial," United States Department of State. Accessed: Apr. 02, 2026. [Online]. Available: https://www.state.gov/releases/office-of-the-spokesperson/2026/02/2026-critical-minerals-ministerial/
[11] "SRD Catalog," *NIST*, Jan. 2025, Accessed: Feb. 18, 2026. [Online]. Available: https://www.nist.gov/srd/srd-catalog
[12] B. Lane *et al.*, "Design, Developments, and Results from the NIST Additive Manufacturing Metrology Testbed (AMMT)," 2016, Accessed: Feb. 18, 2026. [Online]. Available: https://hdl.handle.net/2152/89662
[13] N. Derimow *et al.*, "Evaluation of variations in solution annealing, intercritical annealing, and aging treatments on cobalt-free maraging steels," National Institute of Standards and Technology (U.S.), Gaithersburg, MD, NIST TN 2352, Sep. 2025. doi: 10.6028/NIST.TN.2352.

[14] A. Saville *et al.*, "Priming additively manufactured cobalt-free maraging steels for improved properties through changes to as-built microstructure," National Institute of Standards and Technology (U.S.), Gaithersburg, MD, NIST IR 8582, Jul. 2025. doi: 10.6028/NIST.IR.8582.

[15] T. Maani, N. Mathur, C. Rong, and J. W. Sutherland, "Estimating potentially recoverable Nd from end-of-life (EoL) products to meet future U.S. demands," *Resour. Conserv. Recycl.*, vol. 190, p. 106864, Mar. 2023, doi: 10.1016/j.resconrec.2023.106864.

[16] N. Mathur, T. Maani, C. Rong, and J. W. Sutherland, "Forecasting Rare Earth Element Demands for Clean Energy Technologies with the Bass Diffusion Model," *Procedia CIRP*, vol. 122, pp. 55–60, Jan. 2024, doi: 10.1016/j.procir.2024.01.009.

[17] K. Foster and N. Mathur, "Forecasting demand data for critical materials." National Institute of Standards and Technology, p. 10 files, 281 kB, Jul. 25, 2024. doi: 10.18434/MDS2-3442.

[18] K. Foster and N. Mathur, "Forecasting demand data for critical materials," *Data Brief*, vol. 57, p. 111013, Dec. 2024, doi: 10.1016/j.dib.2024.111013.

[19] N. Mathur, J. W. Sutherland, and S. Singh, "A study on end of life photovoltaics as a model for developing industrial synergistic networks," *J. Remanufacturing*, vol. 12, no. 2, pp. 281–301, Jul. 2022, doi: 10.1007/s13243-022-00111-y.

[20] M. Pease, E. Wallace, H. Reed, V. Martin, and S. Granata, "Supply Chain Traceability: Manufacturing Meta-Framework," National Institute of Standards and Technology, NIST Internal or Interagency Report (NISTIR) 8536 (Draft), Jul. 2025. doi: 10.6028/NIST.IR.8536.2pd.

[21] "Supply Chain Traceability Principles: A Manufacturing Meta-Framework | NCCoE." Accessed: Apr. 02, 2026. [Online]. Available: https://www.nccoe.nist.gov/projects/supply-chain-traceability-principles-manufacturing-meta-framework

[22] L. E. Hillberry and J. P. Rice, "Spectral homogenization techniques for the hyperspectral image projector," in *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXVI*, SPIE, May 2015, pp. 356–363. doi: 10.1117/12.2177180.

[23] J. R. Gilchrist, D. W. Allen, and C. Durell, "IEEE P4001: Progress towards a hyperspectral standard," in *Algorithms, Technologies, and Applications for Multispectral and Hyperspectral Imagery XXV*, SPIE, May 2019, p. 1098602. doi: 10.1117/12.2520190.

[24] R. G. Resmini, K. P. Christiansen, and D. W. Allen, "Unraveling low abundance intimate mixtures with deep learning," in *Algorithms, Technologies, and Applications for Multispectral and Hyperspectral Imagery XXV*, SPIE, May 2019, pp. 250–262. doi: 10.1117/12.2518487.

[25] J. W. Fowler *et al.*, "Absolute energies and emission line shapes of the L x-ray transitions of lanthanide metals," *Metrologia*, vol. 58, no. 1, p. 015016, Jan. 2021, doi: 10.1088/1681-7575/abd28a.

[26] T. Jach, N. Ritchie, J. Ullom, and J. A. Beall, "Quantitative analysis with the transition edge sensor microcalorimeter X-ray detector," *Powder Diffr.*, vol. 22, no. 2, pp. 138–141, Jun. 2007, doi: 10.1154/1.2737466.

[27] "High-resolution X-ray spectrometry of solids using the microcalorimeter X-ray detector - Jach - 2010 - Surface and Interface Analysis - Wiley Online Library." Accessed: Apr. 06,

2026. [Online]. Available: https://analyticalsciencejournals.onlinelibrary.wiley.com/doi/full/10.1002/sia.3598

[28] T. Chen *et al.*, “Rotational dynamics of organic cations in the CH3NH3PbI3 perovskite,” *Phys. Chem. Chem. Phys.*, vol. 17, no. 46, pp. 31278–31286, Nov. 2015, doi: 10.1039/C5CP05348J.

[29] S. V. Rogozhkin *et al.*, “Study of Precipitates in Oxide Dispersion-Strengthened Steels by SANS, TEM, and APT,” *Nanomaterials*, vol. 14, no. 2, p. 194, Jan. 2024, doi: 10.3390/nano14020194.

[30] T. Gnaeupel-Herold, H. J. Prask, J. Barker, F. S. Biancaniello, R. D. Jiggetts, and J. Matejicek, “Microstructure, mechanical properties, and adhesion in IN625 air plasma sprayed coatings,” *Mater. Sci. Eng. A*, vol. 421, no. 1, pp. 77–85, Apr. 2006, doi: 10.1016/j.msea.2005.10.003.

[31] B. Johansson *et al.*, “Challenges and opportunities to advance manufacturing research for sustainable battery life cycles,” *Front. Manuf. Technol.*, vol. 4, Aug. 2024, doi: 10.3389/fmtec.2024.1360076.

[32] D. J. Lyons, J. L. Weaver, and A. C. Co, “Considerations in applying neutron depth profiling (NDP) to Li-ion battery research,” *J. Mater. Chem. A*, vol. 10, no. 5, pp. 2336–2351, 2022, doi: 10.1039/D1TA09639G.

[33] R. M. Lindstrom, “Prompt-Gamma Activation Analysis,” *J. Res. Natl. Inst. Stand. Technol.*, vol. 98, no. 1, pp. 127–133, 1993, doi: 10.6028/jres.098.009.

[34] R. L. Paul, “Improving accuracy, precision, detection limits, and sample throughput in prompt gamma-ray activation analysis using cold and thermal neutrons and element ratios,” *J. Radioanal. Nucl. Chem.*, vol. 318, no. 3, pp. 2273–2278, Dec. 2018, doi: 10.1007/s10967-018-6212-7.

[35] R. L. Paul and H. H. Chen-Mayer, “Determination of fluorine in reference materials by chopped-beam cold neutron prompt gamma-ray activation analysis (CB-CNPGAA),” *J. Radioanal. Nucl. Chem.*, vol. 334, no. 1, pp. 689–696, Jan. 2025, doi: 10.1007/s10967-024-09807-w.

[36] S. Z. Jones *et al.*, “Measurement and modeling of the ability of crack fillers to prevent chloride ingress into mortar,” *Cem. Concr. Compos.*, vol. 81, pp. 109–121, Aug. 2017, doi: 10.1016/j.cemconcomp.2017.05.006.

[37] “ISO/TC 333 - Lithium,” ISO. Accessed: Feb. 17, 2026. [Online]. Available: https://www.iso.org/committee/8031128.html

[38] J. Melcher, J. Stirling, F. G. Cervantes, J. R. Pratt, and G. A. Shaw, “A self-calibrating optomechanical force sensor with femtonewton resolution,” *Appl. Phys. Lett.*, vol. 105, no. 23, p. 233109, Dec. 2014, doi: 10.1063/1.4903801.

[39] J. Kitching *et al.*, “NIST on a Chip: Realizing SI units with microfabricated alkali vapour cells,” *J. Phys. Conf. Ser.*, vol. 723, no. 1, p. 012056, Jun. 2016, doi: 10.1088/1742-6596/723/1/012056.

[40] H. Miao, K. Srinivasan, and V. Aksyuk, “A microelectromechanically controlled cavity optomechanical sensing system,” *New J. Phys.*, vol. 14, no. 7, p. 075015, Jul. 2012, doi: 10.1088/1367-2630/14/7/075015.

[41] A. Agbim, K. A. Schumacher, N. Sharp, R. Paul, and R. Corzo, “Elemental characterization of electronic waste: a review of research methodologies and applicability to the practice of e-

waste recycling," *Waste Manag.*, vol. 187, pp. 91–100, Oct. 2024, doi: 10.1016/j.wasman.2024.07.009.

[42] A. D. Iams, J. S. Zuback, M. R. Stoudt, and C. E. Campbell, "Material challenges in developing a sustainable metal processing infrastructure : workshop report," National Institute of Standards and Technology (U.S.), Gaithersburg, MD, NIST SP 1500-32, Sep. 2025. doi: 10.6028/NIST.SP.1500-32.

Appendix A. List of Symbols, Abbreviations, and Acronyms

ACerS
American Ceramic Society

AI/ML
Artificial Intelligence and Machine Learning

AM
Additive Manufacturing

API
Application Programming Interface

CALPHAD
Calculation of Phase Diagrams

CMM
Critical Minerals and Materials

DFT
Density Functional Theory

DOE
Department of Energy

EO
Executive Order

EoU
End-of-Use

EV
Electric Vehicle

FAIR
Findable, Accessible, Interoperable, and Reusable

ICME
Integrated Computational Materials Engineering

ICP-MS
Inductively Coupled Plasma Mass Spectrometry

ICP-OES
Inductively Coupled Plasma Optical Emission Spectroscopy

ITC
Isothermal Titration Calorimetry

INAA
Instrumental Neutron Activation Analysis

ISO
International Organization for Standardization

JARVIS
Joint Automated Repository for Various Integrated Simulations

LCA
Life Cycle Assessment

MFA
Material Flow Analysis

MGI
Materials Genome Initiative

MML
Material Measurement Laboratory

NAA
Neutron Activation Analysis

NCCoE
National Cybersecurity Center of Excellence

NCNR
NIST Center for Neutron Research

NDP
Neutron Depth Profiling

OEM
Original Equipment Manufacturer

PGAA
Prompt Gamma Activation Analysis

PGM
Platinum Group Metal

PPB
Part per Billion

PV
Photovoltaic

REE
Rare Earth Element

RD
Reference Data

RM
Reference Material

SAMAD
System for AM Alloy Development

SCRM
Supply Chain Risk Management

SEM-EDS
Scanning Electron Microscopy - Energy Dispersive X-ray Spectroscopy

SI

International System of Units

SIMS
Secondary Ion Mass Spectrometry

SRM
Standard Reference Material

TEM
Transmission Electron Microscopy

TGA-GC-MS
Thermogravimetric Analysis - Gas Chromatography - Mass Spectrometry

TIR
Total Internal Reflection

USGS
United States Geological Survey

VAMAS
Versailles Project on Advanced Materials and Standards

XRF
X-ray Fluorescence Spectroscopy

Appendix B. Workshop Agenda

Time (ET)	Speaker	Topic
1:00-1:05	Kelsea Schumacher	Welcome and intro
1:05-1:35	Roderick Eggert	Keynote: Critical Minerals and Materials: Framing the Policy Discussion
1:35-1:40	Jeff Fagan	Coordinating potential pre-standards activities through VAMAS
1:40-1:45	John Bonevich	ISO standards
1:45-2:00	Michael Winchester	SRMs for critical minerals and materials
2:00-2:15	Craig Brown	Neutron measurements to advance CMM research
2:15-2:20	David Allen	Standards development for hyperspectral imaging related to CMMs
2:20-2:30	Break	
2:30-2:45	Boris Wilthan	Thermophysical Property data for metal systems
2:45-3:00	Nehika Mathur	Quantification and characterization of CMMs in emerging technologies, implications of recovery
3:00-3:15	Abheek Chatterjee	Secondary Materials Market development related to Critical Materials
3:15-3:20	Tom Moffat	Thrifty use of precious metal for applications in electrochemical science, technology, and catalysis
3:20-3:25	Gordon Shaw	Characterizing mass and density of critical mineral particles present in coal fly ash
3:25-3:40	Nik Hrabe	Development of cobalt-free maraging steel using additive manufacturing and novel heat treatments to promote new strengthening mechanisms
3:40-3:45	Fan Zhang	Enabling critical materials development through advanced manufacturing, characterization, and data-driven solutions
3:45-3:50	Howie Joress	Autonomous methods and high entropy alloys
3:50-4:00	Break	
4:00-4:05	Terrence Jach	Quantitative analysis of rare earths with X-ray Microcalorimetry
4:05-4:20	Nick Sharp	Quantitative elemental analysis of electronic waste
4:20-4:35	Jamie Weaver	Recovery of CMMs from Li batteries and battery material scrap
4:35-4:50	James Zubak	Impurity tolerant alloy design, critical material recovery, critical material substitution
4:50-4:55	Avery Baumann	Thermodynamic Quantification for Critical Materials Separation and Recovery from Microelectronic Waste Streams
4:55-5:00	Ashley Hartwell	Measurement Science for Microelectronic Recovery
5:00-5:05	Kelsea Schumacher	Wrap up

Appendix C. Alignment of CMM Lists with NIST SRM 3100 Series.

The NIST SRM 3100 series provides single-element standard solutions with certified values traceable to the International System of Units (SI). These materials enable commercial producers and researchers to establish measurement traceability through high-performance inductively-coupled plasma optical emission spectrometry (ICP-OES).

CMM	CMM List Source	NIST SRM 3100 Series	NIST SKU	Notes
Aluminum	DOE/USGS	Aluminum	3101a	
Antimony	USGS	Antimony	3102a	
Arsenic	USGS	Arsenic	3103a	
Barite	USGS	—	—	No NIST SRM
Beryllium	USGS	Beryllium	3105a	
Bismuth	USGS	Bismuth	3106	
Boron	USGS	Boron	3107	
Cerium	USGS	Cerium	3110	
Cesium	USGS	Cesium	3111a	
Chromium	USGS	Chromium	3112a	
Cobalt	DOE/USGS	Cobalt	3113	
Copper	DOE/USGS	Copper	3114	
Dysprosium	DOE/USGS	Dysprosium	3115a	
Electrical Steel	DOE	—	—	No NIST SRM
Erbium	USGS	Erbium	3116a	
Europium	USGS	Europium	3117a	
Fluorine	DOE	—	—	No NIST SRM
Fluorspar	USGS	High-Grade Fluorspar	180	Not 3100 series
Gadolinium	USGS	Gadolinium	3118a	
Gallium	DOE/USGS	Gallium	3119a	
Germanium	USGS	Germanium	3120a	
Hafnium	USGS	Hafnium	3122	
Holmium	USGS	Holmium	3123a	
Indium	USGS	Indium	3124a	
Iridium	DOE/USGS	—	—	No NIST SRM
Lanthanum	USGS	Lanthanum	3127a	
Lead	USGS	Lead	3128	
Lithium	DOE/USGS	Lithium	3129a	
Lutetium	USGS	Lutetium	3130a	
Magnesium	DOE/USGS	Magnesium	3131a	
Manganese	USGS	Manganese	3132	
Metallurgical Coal	USGS	—	—	No NIST SRM

CMM	CMM List Source	NIST SRM 3100 Series	NIST SKU	Notes
Natural Graphite	DOE/USGS	—	—	NIST has USGS24 (Carbon Isotopes)
Neodymium	DOE/USGS	Neodymium	3135a	
Nickel	USGS	Nickel	3136	
Nickel (high-purity)	DOE	—	—	
Niobium	USGS	Niobium	3137	
Palladium	USGS	Palladium	3138	
Phosphate	USGS	—	—	Multiple phosphate SRMs available
Platinum	DOE/USGS	Platinum	3140	
Potash	USGS	—	—	No NIST SRM
Praseodymium	DOE/USGS	Praseodymium	3142a	
Rhenium	USGS	Rhenium	3143	
Rhodium	USGS	Rhodium	3144	
Rubidium	USGS	Rubidium	3145a	
Ruthenium	USGS	—	—	No NIST SRM
Samarium	USGS	Samarium	3147a	
Scandium	USGS	Scandium	3148a	
Silicon	DOE/USGS	Silicon	3150	
Silicon Carbide	DOE	—	—	No NIST SRM
Silver	USGS	Silver	3151	
Tantalum	USGS	Tantalum	3155	
Tellurium	USGS	Tellurium	3156	
Terbium	DOE/USGS	Terbium	3157a	
Thulium	USGS	Thulium	3160a	
Tin	USGS	Tin	3161a	
Titanium	USGS	Titanium	3162a	
Tungsten	USGS	Tungsten	3163	
Uranium	USGS	Uranium	3164	
Vanadium	USGS	Vanadium	3165	
Ytterbium	USGS	Ytterbium	3166a	
Yttrium	USGS	Yttrium	3167a	
Zinc	USGS	Zinc	3168a	
Zirconium	USGS	Zirconium	3169	