

Article

Proposing Safety Metrology for Loss Prevention in the Process Industries: An Interdisciplinary Bridge and Its Theoretical Pillars Towards Sustainable Risk Management

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Abstract

The qualitative and experience-dependent nature of traditional safety management in high-hazard process industries (e.g., chemical, petrochemical, oil & gas) poses significant challenges to scientific decision-making and cross-domain benchmarking. To address this, we propose and systematically construct Safety Metrology as a nascent sub-discipline of safety science with direct relevance to process safety engineering. Through a comprehensive analysis of disciplinary evolution, societal demands, and theoretical foundations, this study develops a conceptual framework characterized by ‘benchmarking, consistency, and reliability’, supported by a four-dimensional theoretical pillar (philosophy, safety science, metrology, and interdisciplinarity). The findings demonstrate that Safety Metrology provides the methodological bedrock for achieving quantifiable, comparable, and actionable safety management in complex process systems, thereby facilitating a paradigm shift towards data-driven safety governance in complex systems and contributing to sustainable risk management in high-hazard industries.

Keywords: safety metrology; process safety; quantitative risk assessment (QRA); loss prevention; sustainable risk management; safety governance

1. Introduction

Traditional safety management in the process industries has long relied on qualitative analysis and experiential judgment, suffering from the inherent limitation of “vague assessments hindering precise interventions.” This deficiency primarily manifests in three aspects. First, there is a lack of scientific rigor in decision-making. Traditional qualitative methods, such as the Delphi method and expert scoring, are susceptible to cognitive biases, leading to significant discrepancies in risk judgments among different evaluators for the same hazard [1]. In process safety, this is evident in the subjective scoring of risk matrices during HAZOP or LOPA studies. In the petrochemical industry, for instance, divergent expert experiences often cause confusion in risk classification standards, frequently resulting in “different assessments for the same risk.” This directly leads to misallocation and wastage of safety resources [2]. Second, cross-domain and cross-plant risk benchmarking is ineffective. Although frameworks like ISO 31000 [3] provide general processes, the absence of a unified quantitative benchmark means fundamental differences exist in how “high risk” is defined across industries (e.g., risk thresholds differ markedly between the oil and construction



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industries). Concurrently, inconsistent accident statistical calibers among enterprises and even between similar units in different plants (e.g., “lost time injury rate” vs. “accident frequency rate” cannot be directly converted) severely impede the horizontal transfer of risk prevention and control experiences across industries and scenarios.

Furthermore, the problem of lagging dynamic risk response is prominent. Experience-dependent management struggles to adapt to rapidly changing environments. A typical example is process safety emergency response plans, which are often based on historical data. However, in the context of process upsets or novel operating conditions, the frequency and intensity of extreme events have surpassed historical experience. *The Global Assessment Report* (GAR2023) [4] points out that when disaster intensity deviates significantly from historical benchmarks, the vulnerability of emergency response systems increases substantially. Existing emergency response levels, material reserve plans, and rescue strategies may all fail, urgently necessitating the establishment of dynamic adjustment mechanisms based on real-time data. These issues collectively highlight the path dependency on experiential judgment in traditional safety management and its limitations, underscoring the urgency of introducing more scientific and quantifiable management methodologies to prevent major accidents and losses in the process industries. Furthermore, the integration of Safety Metrology aligns with the emerging paradigm of sustainable risk management, which emphasizes long-term system resilience, resource efficiency, and environmental stewardship alongside traditional safety goals. This approach supports the transition towards more sustainable industrial practices by enabling data-driven prevention, optimizing safety resource allocation, and reducing the lifecycle impacts of accidents.

Currently, both academia and industry have recognized the limitations of traditional safety management and have begun exploring the application of quantitative methods. The risk matrix method was first proposed in 1995 by the Acquisition Engineering Group of the US Air Force Electronic Systems Center [5]. It is a risk assessment and management method based on the entire acquisition lifecycle, with its core logic being the simplification of complex risks into actionable numerical indicators, providing a scientific basis for risk control. It is now widely used in chemicals, engineering, occupational safety, and other fields. Its application in process safety (e.g., layer of protection analysis—LOPA) underscores the need for reliable input data. The fact that World Metrology Day in 2012 first adopted “Metrology for Safety” as its annual theme [6] marked a symbolic event, signifying the entry into a new phase of systematic exploration into the integration of metrology and safety. The EU’s “RiskGONE” project attempted to build a cross-industry risk database [7], but suffered from poor data compatibility due to the lack of a unified metrological benchmark. Domestic research has focused on developing quantitative models for specific scenarios, such as FTA-BN-based fire safety assessment for civil aircraft and analysis of influencing factors in airport runway incursion accidents [8,9]. In the process industries, similar models are used for quantitative risk assessment (QRA), fire and explosion modeling, and consequence analysis. However, these studies are often confined to single domains and have not yet formed a universal theoretical framework applicable to the fundamental measurement challenges in process safety. In summary, existing research exhibits three significant shortcomings: Firstly, interdisciplinary integration is weak. Secondly, there is a lack of standardization. Thirdly, dynamic adaptability is insufficient. These problems highlight the urgency of constructing a systematic theory of safety metrology grounded in the needs of process industries.

The core limitations of existing research are primarily manifested in three critical gaps. Firstly, at the theoretical level, the absence of a systematic framework deeply integrating metrological principles into safety science has resulted in a weak methodological foundation. As noted by Aven and Zio [10] in *Reliability Engineering & System Safety*, the field of

risk analysis suffers from significant “conceptual and methodological fragmentation,” with substantial disparities in how different disciplines understand and quantify risk. This fragmentation is particularly problematic when attempting to benchmark safety performance across different process plants. Secondly, in terms of methodological standardization, the measurement of safety parameters critical to loss prevention, such as gas concentration, pressure, temperature, and vibration, lacks a well-established standardized system and traceability assurance mechanism, leading to poor comparability of data generated across studies. This severely hinders the systematic accumulation and effective iteration of safety knowledge. Finally, regarding disciplinary positioning, the academic attributes, research scope, and core connotations of “safety metrology” remain undefined, a fundamental gap that directly impedes its establishment and development as an independent disciplinary branch with practical utility for process safety engineers.

Against this backdrop, this study seeks to fill these interdisciplinary gaps by systematically constructing the theoretical foundation of safety metrology with a focus on applications in loss prevention for the process industries. The central thesis of this research is that the establishment of safety metrology fundamentally lies in driving a paradigm shift in safety management from “experience-driven” to “data-driven.” This paradigm transition is realized through three core mechanisms: first, the quantitative characterization of risk, which employs probabilistic risk indices and other forms to transform abstract risks into computable parameters, thereby addressing the challenge of “ambiguous evaluation”; second, the precise optimization of decision-making, leveraging algorithmic models to achieve optimal allocation of safety resources; and third, dynamic evaluation and iteration, utilizing tools such as machine learning to predict the effectiveness of interventions in real time. For instance, probabilistic graphical models like Bayesian networks can convert discrete risk factors into continuous computable variables, while standardized frameworks such as *NIST SP 800-82* [11] provide support for establishing cross-industry safety benchmarks. In a process plant context, this could mean standardizing the measurement and reporting of parameters like lower flammability limit (LFL) percentage or safety instrumented system (SIS) test failure rates. To systematically elaborate on this paradigm, the structure of this paper is organized as follows: Section 1 defines the core concepts of safety metrology, clarifies the foundational connotations of “safety” and “safety science,” distinguishes the hierarchical relationship between “safety measurement” and “safety metrology,” and analyzes the emergence logic of safety metrology from the perspective of disciplinary evolution. Section 2 examines its establishment background from dual perspectives of disciplinary evolution and societal needs, addressing both the metrological demands of safety science development and the disciplinary expansion needs of metrology, as well as practical requirements such as the refinement of safety management, multidimensional safety governance, and intelligent safety decision-making in high-hazard industries. Section 3 constructs a four-dimensional theoretical system encompassing philosophical foundations, principles of safety science, metrological frameworks, and interdisciplinary support. The paper clarifies the disciplinary positioning and research scope, providing a foundation for establishing unified safety metrology standards and promoting the transition of safety science toward precision and intelligence, specifically within the domain of process safety and loss prevention.

2. Conceptual Delineation of Safety Metrology

2.1. Safety and Safety Science

As an independent disciplinary domain, Safety and its related research have witnessed continuous evolution in their conceptual connotations and theoretical paradigms. The academic community widely references the dualistic framework proposed by Hollnagel [12]

in his seminal work *Safety-I and Safety-II: The Past and Future of Safety Management* to define “safety”. This research identifies a paradigm shift in the understanding of safety from “Safety-I” to “Safety-II”. The conventional perspective (Safety-I) characterizes safety as “the minimization of things going wrong,” concentrating primarily on accident prevention and risk mitigation. This aligns with the traditional focus of process safety on preventing major accidents like fires, explosions, and toxic releases. In contrast, the contemporary perspective (Safety-II) redefines safety as “the maximization of things going right,” reflecting a transition in research emphasis from averting adverse events to comprehending and assuring system reliability and resilience in routine operations [10]. In process terms, this translates to ensuring operational integrity and the reliable performance of safety-critical systems. Under this theoretical structure, Safety Metrology provides critical quantitative tools for measuring system resilience and process reliability. By developing metrics such as the Recovery Time Index, Adaptive Capacity Metric, and Functional Retention Rate, it transforms the abstract concept of resilience into actionable engineering parameters. Specifically, the Recovery Time Index precisely measures the speed at which a system recovers from disturbances such as a process upset; the Adaptive Capacity Metric evaluates the system’s flexibility in learning, improvement, and strategy adjustment; and the Functional Retention Rate quantifies the extent to which critical performance is maintained under extreme conditions like overpressure or high temperature. These metrics collectively establish a scientific metrological foundation for the design, optimization, and validation of resilience in complex systems like chemical process plants. Ultimately, this approach enables a paradigm shift from qualitative assessments to data-driven resilience management, fostering robust system performance in dynamic and uncertain environments. The fundamental conception of safety is broadened to include a composite condition embracing accident prevention, risk management, system reliability, human factors, organizational safety culture, and engineering practices, all of which are central to process safety management.

Safety Science, as an interdisciplinary field dedicated to the systematic examination of safety phenomena, possesses a clearly delineated disciplinary framework and research domain. Hale and Hovden [13], in their article *Management and culture: The third age of safety*, methodically analyzed the progression of safety research and characterized safety science as an integrative discipline focused on accident prevention and risk control. Their study outlined the principal research areas constituting the foundational pillars of safety science, which include: accident causation theories and modeling (e.g., Reason’s Swiss Cheese Model); methodologies for risk assessment and management; development and refinement of safety management systems and standards; examination of safety culture and organizational conduct; and the implementation of human factors engineering and ergonomics. Process safety is a major applied branch of safety science.

Ongoing scholarly investigation has progressively reinforced the disciplinary autonomy and theoretical sophistication of safety science. Modern scholarship conceptualizes safety science as a discipline fundamentally aimed at “safety promotion”. It employs a dual methodological approach—incorporating both proactive strategies (e.g., resilience engineering) and reactive analyses (e.g., accident causation investigation)—to elucidate the patterns governing the emergence and evolution of safety, and to formulate efficacious intervention strategies. Its investigative purview now encompasses safety considerations across all system typologies. Within formal disciplinary taxonomies (e.g., China’s subject classification system), “Safety Science” is frequently construed in a restricted sense, emphasizing occupational and public safety. Conversely, the modern safety science debated within academic circles represents a more comprehensive and dynamically evolving disciplinary construct. It assimilates multiple specialized sub-fields and perpetually adapts

and refines itself in response to the escalating diversification and pervasiveness of societal safety exigencies.

2.2. *Safety Metrology and Its Disciplinary Definition*

Based on the broad definition of safety and metrology [14], Safety Metrology can be defined as a measurement science centered on quantifying safety states. Its core mission is to ensure the accuracy and comparability of safety risk assessment and management by establishing measurement benchmarks, standards, and traceability systems for safety-related physical, chemical, biological, and composite quantities. Unlike safety detection science, safety metrology does not focus on specific detection technologies (such as sensor or instrument development) but emphasizes the standardization, traceability, and international equivalence of measured values—for instance, ensuring consistent measurement results for toxic gas concentrations across laboratories worldwide. For process plants, this ensures that a ‘LFL’ reading in one control room means the same thing as in another, which is critical for automated safety actions. Simultaneously, safety metrology differs from safety evaluation science, which focuses on risk classification and countermeasure recommendations, whereas safety metrology provides foundational quantitative support, such as accurately measuring explosion limit concentrations to inform hazardous area zoning, thereby establishing a unique disciplinary position within safety science.

Safety Metrology is a theoretical and methodological discipline that studies the definition of safety-related quantities, measurement methods, standard systems, and data applications. Its essence lies in addressing fundamental issues of benchmarking, consistency, and decision-making reliability in the quantification of safety states through the integration of metrological principles and safety science. Safety Metrology not only represents the expansion of metrology into the safety domain, but also serves as a critical “bridge”—functioning both as a transformative medium connecting abstract safety theories with concrete engineering practices, and as a core methodological framework driving safety science toward greater scientific rigor and precision. It aims to establish, maintain, and continuously develop a set of quantitative benchmarks, standardized measurement methods, traceability systems, and uncertainty evaluation theories for “safety states” and “risk levels,” thereby providing foundational metrological support for the comparability, mutual recognition, and scientific rigor of safety data. Ultimately, it seeks to realize “measurable, calculable, and optimizable” safety management, as illustrated in Figure 1. As a sub-discipline of safety science, the scope of safety metrology encompasses all safety-related fields, interacting with and mutually reinforcing other safety disciplines to collectively advance the development of safety science.

The core connotation of safety metrology is embodied in the “Three Characteristics and One Goal.” It ensures “benchmarking” by establishing international or national benchmarks for safety quantities (e.g., absolute measurement methods for the lower explosion limit of dust), with the achievement of this goal relying on the support of a safety metrological value system; achieves “consistency” in measurement results across time, space, and institutions (e.g., mutual recognition of global mine gas concentration monitoring data), which requires standardized measurement methods provided by safety measurement methodology; and enhances “reliability” through uncertainty analysis (e.g., error control in radiation monitoring data at nuclear power plants), with the attainment of this goal depending on the assurance of safety data quality governance. Furthermore, the path from measurement uncertainty to decision confidence is crucial in ensuring that safety measurements not only reflect accuracy but also provide a basis for informed decisions. This is achieved by systematically analyzing measurement uncertainties and applying them to decision-making models, which in turn strengthens the confidence in the safety

decisions made, ensuring that safety protocols are both robust and trustworthy. Ultimately, its goal is to transform quantitative results into actionable management parameters (e.g., designing shift rotation systems based on cumulative noise exposure), thereby promoting the “scientification and accuracy” of safety decision-making; the achievement of this goal requires collaborative support from all research domains, including the construction of a safety metrological value system, safety measurement methodology, safety metrological standard systems, and safety data quality governance.

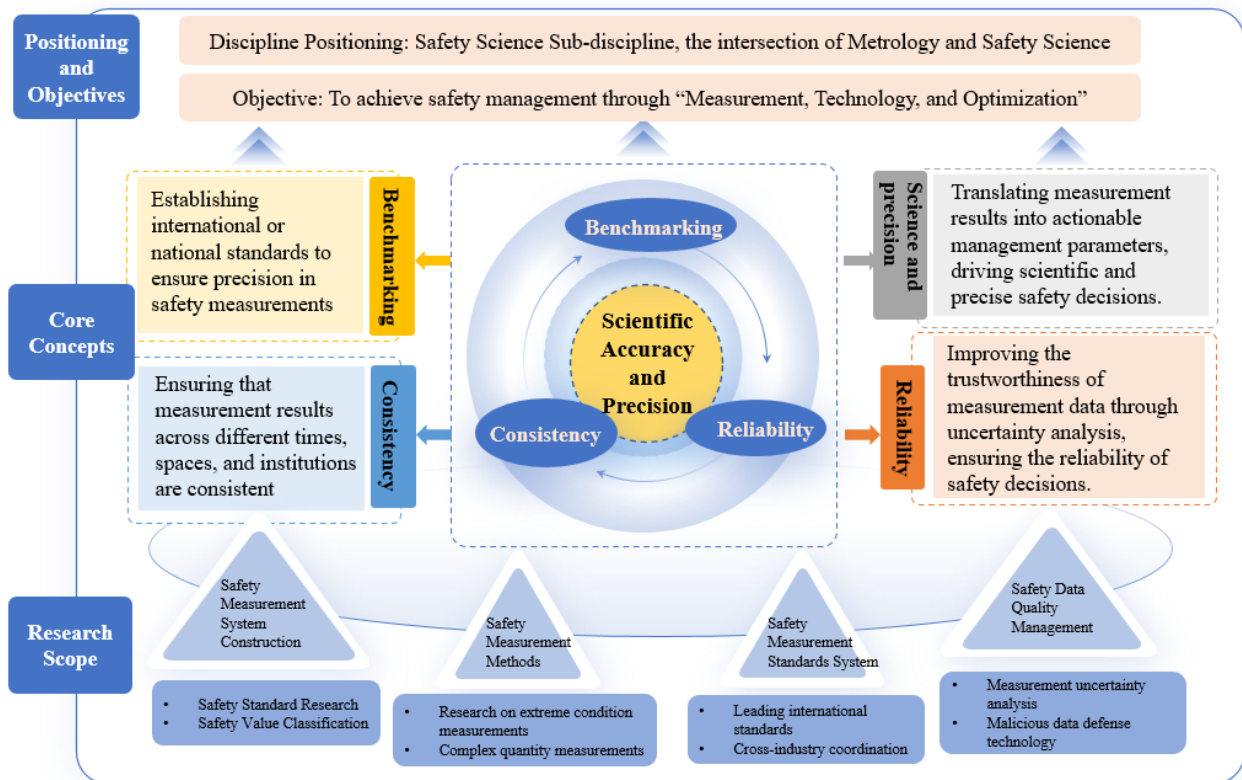


Figure 1. The Preliminary Research Content of Safety Metrology.

The research scope of Safety Metrology focuses on crucial areas in process safety and loss prevention, aimed at enhancing the safety and reliability of industrial operations. It involves the development of safety benchmarks and standards, including the introduction of new metrological units (such as the “safety efficacy index”) and the establishment of traceable reference values for critical parameters like corrosion rates in specific process streams. Safety Metrology also develops measurement methodologies for extreme industrial conditions, such as high-temperature, highly corrosive environments, and hazardous chemical processes, with applications like machine learning to improve safety in pressurized water reactors (PWRs). Additionally, it encompasses the creation of international standards for calibration and performance verification of Safety Instrumented System (SIS) sensors, ensuring accuracy and reliability in safety data and risk assessments. Furthermore, Safety Metrology addresses data quality governance, focusing on measurement uncertainty analysis and the application of technologies like blockchain to safeguard the integrity of safety data, ensuring accurate decision-making in accident statistics and other safety-critical data. These efforts aim to introduce new quantities, units, traceability systems, and uncertainty formulations tailored specifically to the safety domain, contributing to the establishment of a scientific and precise safety quantification system that supports more effective safety management and loss prevention strategies in industrial settings.

Safety Science provides the theoretical foundation for studying safety issues, while Safety Metrology serves as a crucial technical supporting branch. The interconnectedness between the two is fully demonstrated in practical applications. For instance, in the industrial production sector, measuring equipment failure rates enables the prediction of system risks and facilitates proactive maintenance measures. In process plants, precise measurement of vibration spectra can predict pump or compressor failures, preventing unplanned shutdowns and potential loss of containment. In the field of public safety, modeling and analysis based on crime data can optimize police force deployment and enhance prevention and control efficiency. Moreover, in the emerging field of sustainable energy, Safety Metrology plays a critical role in the safe and efficient operation of underground energy storage systems, such as pumped hydro storage (UPHES) and compressed air energy storage (CAES), as well as geothermal systems. Accurate measurement and traceability are essential to monitor these systems' performance, ensuring their reliability and safety over long periods. In infrastructure monitoring, Safety Metrology is used to assess the integrity of critical structures such as bridges and dams, helping prevent catastrophic failures and ensuring long-term operational safety. These practices not only validate the value of theoretical frameworks but also highlight the significance of methodological approaches in addressing real-world challenges. A comparative analysis of the definitions and core connotations of relevant key terms is presented in Table 1.

Table 1. Definitions and Core Connotations of Safety, Safety Science, Safety Measurement, and Safety Metrology.

Concept	Definition	Core Connotations
Safety	A state in which a system is free from unacceptable adverse effects caused by internal or external factors [15].	Relativity: Safety standards evolve with societal awareness. Multidimensionality: Encompasses personal, information, public, and national security domains. Dynamism: Non-static and non-final, requiring continuous maintenance. Systematicity: Results from the synergy of technology, management, and human factors, necessitating a comprehensive “prevention-response-recovery” chain mechanism. Interdisciplinarity: Integrates theories and methods from multiple disciplines to build theoretical frameworks and systematic risk prevention and control systems.
Safety Science	The fundamental scientific principles of universal significance, derived through observation, practice, induction, abstraction, and summarization, focusing on protecting humans from physical and mental harm caused by external adverse factors during life, production, and survival activities [16].	Practice-Oriented: Aims fundamentally to solve real-world safety problems. Dynamic Adaptability: Continuously optimizes technical means and management strategies to address emerging risks and enhance safety resilience. Human-Centric Core: Emphasizes the impact of human behavior, cognition, and organizational culture on safety performance, promoting the coordinated development of “technology-management-culture.”

Table 1. *Cont.*

Concept	Definition	Core Connotations
Safety Measurement	The process of applying scientific methods, techniques, and tools to conduct quantitative measurement, assessment, and analysis of various safety-related elements, states, and risks.	Technical Precision: Based on high-precision measurement technologies and standardized methods, utilizing advanced instruments for accurate quantification of safety parameters. System Synergy: Integrates four key elements—human operation, equipment status, environmental conditions, and management processes—to build a multi-dimensional, coordinated safety measurement and monitoring system. Risk Pre-Control: Enables early identification and proactive prevention of hazards through trend analysis and early-warning modeling of dynamic monitoring data. Standardization & Normativity: Strictly adheres to national/industry metrological standards to ensure accuracy, comparability, and legal validity of results. Intelligent Development: Integrates new technologies like IoT and big data to advance safety measurement towards real-time and intelligent capabilities. Methodological Systematism: Establishes a complete methodological framework including measurement specifications, analytical models, and evaluation criteria.
Safety Metrology	An interdisciplinary science studying the methods for quantitative measurement, assessment, and analysis of safety-related elements, aiming to enhance the precision and reliability of safety management through standardized measurement, data modeling, and decision optimization.	Data Scientism: Integrates modern statistical theory and computer processing for precise data collection, intelligent analysis, and visualization. Domain Universality: Develops technical frameworks applicable across industries like industrial safety, environmental monitoring, and public emergency response. Technological Advancement: Continuously incorporates advancements in IT (e.g., IoT, AI) to drive methodological innovation. Decision Support: Provides objective, quantitative foundations for safety management decisions, shifting from experience-based to data-driven approaches.

By comparing with existing disciplines, the irreplaceability of Safety Metrology is primarily reflected in its core characteristics of fundamentality, standardization, and traceability. Specific differences are detailed in Table 2.

Safety Metrology, as the “underlying infrastructure” of safety science, holds unique value. Its standardized value system serves as a prerequisite for the reliability of detection technologies and the scientific validity of evaluation conclusions, particularly in the data-driven management of process safety. Safety Metrology is poised to play a pivotal role in defining new quantities, units, traceability chains, and uncertainty formulations in the safety domain, though much of this work is still in its conceptual and developmental stages. In the coming phases of research, we aim to establish standardized quantities and units specific to safety metrics, such as defining a universal ‘process safety performance unit’ that can be applied across different industries. Additionally, a robust traceability system will be

developed to link safety measurements to internationally recognized standards, ensuring consistency and comparability of safety data across different regions and sectors. This will be complemented by the creation of uncertainty formulations that can accurately assess the variability in safety measurements, providing a solid foundation for the reliability of safety data.

Table 2. The specific distinctions between Safety Metrology, Safety Testing, and Safety Assessment.

Comparative Dimension	Safety Metrology	Safety Testing	Safety Assessment
Core Objective	Establish scientific benchmarks and standard systems for safety quantities	Develop detection technologies and equipment for specific scenarios	Evaluate system risk levels based on quantitative data
Research Level	Scientific Level (Unit definition, value traceability)	Technical Level (Sensor development, instrumentation)	Application Level (Risk modeling, decision support)
Key Outputs	International standard units, measurement specifications, traceability methods	Testing instruments, monitoring systems, diagnostic algorithms	Risk assessment reports, safety classification systems
Data Role	Provides standardized, traceable reference data	Generates raw detection data	Utilizes metrological data to complete risk quantification
Irreplaceability	Ensures comparability and credibility of cross-domain safety data	Enables real-time monitoring capability for specific scenarios	Acts as a bridge linking data and decision-making

Safety Metrology distinguishes itself from existing safety science and applied metrology by addressing key gaps that current methodologies cannot fill. Traditional safety science often relies on qualitative assessments and lacks standardized measurement systems, leading to fragmented and non-comparable data. While applied metrology in safety provides tools for specific measurement tasks, it does not offer a unified framework that ensures global comparability and traceability across industries and regions. Safety Metrology, on the other hand, integrates standardization, traceability, and uncertainty analysis, establishing a global measurement system that guarantees the consistency and reliability of safety data. It not only supports Safety Testing and Safety Assessment by providing a solid foundation for accurate, traceable measurements but also ensures that the data used in risk evaluations is scientifically valid and universally applicable. By bridging these gaps, Safety Metrology transforms safety management, making it data-driven, scientifically rigorous, and universally comparable across industries and borders, which is crucial for enhancing the effectiveness and reliability of safety protocols.

3. Founding Background of Safety Metrology

3.1. Background of Disciplinary Evolution

3.1.1. The Metrological Demand in the Development of Safety Science

With the in-depth development of modern safety science [17], its research paradigm is shifting from experience-driven to data-driven, leading to increasingly significant demands for quantitative, dynamic, and multidimensional measurements. This presents both opportunities and challenges for the establishment of Safety Metrology.

In terms of quantification, traditional safety management relies on experiential judgment and vague qualitative descriptions to assess safety conditions, lacking unified measurement standards. This results in subjective and arbitrary assessments, leaving corporate safety decisions without precise data support. Modern safety standards, however, require the construction of quantifiable safety performance indicators, such as accident rates and exposure limit compliance rates. Effectively applying these indicators faces challenges related to their definition, measurement methods, and data comparability. In process safety, key performance indicators (KPIs) like ‘pressure safety valve (PSV) testing overdue rate’ or ‘SIS demand rate’ require clear, standardized definitions of measurement to be meaningful. Taking dust concentration measurement in the occupational health field as an example, it requires the integration of sampling standards and metrological calibration techniques

to ensure data accuracy. Similarly, measuring fugitive emissions or pipeline leak rates for environmental and safety compliance requires rigorous metrological approaches. As an emerging interdisciplinary field, Safety Metrology integrates safety science and metrology to address these issues, providing crucial support for the quantitative assessment of safety performance and promoting the enhancement of corporate safety management levels.

Regarding dynamism, industrial systems are becoming increasingly complex, such as chemical processes and smart grids. Traditional periodic inspection models are lagging and cannot meet the needs of dynamic risk management. Although high-precision sensors and IoT technologies enable real-time monitoring of system status, their application faces challenges such as the selection of measurement frequency, signal noise interference, and the setting of state warning thresholds. Metrology provides the theoretical basis and methodological support to address these issues, for instance, by optimizing measurement frequency, suppressing signal noise, and scientifically setting warning thresholds. Taking a coal mine gas monitoring system as an example, the measurement uncertainty analysis from metrology can enhance the reliability of explosion risk warnings. A process industry equivalent is the real-time monitoring of hydrogen concentration in battery rooms or reformer units, where precise threshold setting is critical. Establishing a safety metrology system can standardize the safety measurement process, promote the deep integration of safety science and metrology, and drive the transition of safety management towards a more scientific and precise model. Amid evolving dynamics, security challenges in emerging risk domains—such as cybersecurity, biosecurity, and low-altitude security—are growing increasingly acute. These domains exhibit highly dynamic and complex risk characteristics that render conventional qualitative assessment methods insufficient for real-time monitoring and management. The development of safety metrology will not only address the gap in dynamic quantitative assessment for emerging risks but also propel safety management from experiential judgment to data-driven decision-making, thereby establishing a scientific foundation for emerging technology adoption and risk governance.

In terms of multidimensionality, contemporary safety risks exhibit characteristics of multi-factor coupling. Under the “Human–Machine–Environment–Management” model [18], traditional single indicators cannot comprehensively and accurately reflect a system’s safety level. Metrology can provide normalization methods for multi-source data and utilize weighting methods, such as the Analytic Hierarchy Process (AHP), to construct comprehensive safety indices. This is directly applicable to creating a composite ‘process safety health index’ from parameters like corrosion rate, safety system availability, and near-miss frequency. As safety science evolves, the demands for the accuracy and comprehensiveness of safety assessments increase. The establishment of Safety Metrology meets this demand. It enables the accurate assessment of system safety levels, facilitates the formulation of safety measures, and provides a scientific basis for safety supervision. It is an inevitable choice to adapt to the developmental needs of safety science and ensure the safe operation of systems, especially complex chemical process systems.

The urgent need for quantitative, dynamic, and multidimensional measurements in modern safety science necessitates the establishment of Safety Metrology. This field systematically addresses measurement problems in the safety domain, promotes the deep integration of safety science and metrology, and provides support for industrial safety and social stability. The trend of the International Society of Safety Science (ISSS) promoting the inclusion of safety metrology in scientific evaluation systems further indicates an urgent need to integrate risk quantification, international standardization, and interdisciplinary methods to establish a comprehensive Safety Metrology system. This will fill the gap in the quantitative assessment of the safety dimension within scientific evaluation, enabling more comprehensive scientific evaluation and risk management. For the process indus-

tries, this could lead to internationally accepted metrics for comparing the intrinsic safety performance of different technologies or plants. Recent studies, such as Guo et al. [19], on underground water storage space and thermal reservoir models in abandoned mines, further exemplify the practical application of safety metrology in areas like sustainable infrastructure development and energy storage.

3.1.2. The Need for Disciplinary Expansion of Metrology

Traditional metrology has established a methodological system in fields such as physics and chemistry. The International System of Units (SI) [20] and guidelines for evaluating measurement uncertainty ensure unified measurement standards and reliability assessment. With the growing demand for scientific quantification and standardization in the safety domain, there is both feasibility and necessity for the migration of traditional metrological achievements into this field. Safety Metrology integrates traditional metrological methods with safety risk assessment techniques, employing quantitative approaches to study safety issues.

The metrological paradigm of “Value Definition [21]—Measurement Method—Traceability Chain” is of great significance for solving the standardization problems of safety parameters. The safety field involves numerous parameters, making accurate measurement and standardization crucial. The International Bureau of Weights and Measures (BIPM) establish traceability systems through certified reference materials, ensuring the comparability of data from laboratories worldwide and laying the foundation for the standardization of safety indicators. In process safety, this could underpin the standardization of flare radiation measurement or the calibration of combustible gas detectors used in area classification.

In safety decision-making processes, such as crucial decisions on whether to suspend operations for rectification, the credibility of measurement data plays a key role. Uncertainty evaluation methods in metrology, such as the Guide to the Expression of Uncertainty in Measurement (GUM) [22], can quantify the impact of factors like sensor errors and sampling biases on risk assessment. In practical safety monitoring, various measurement equipment and sampling methods inherently possess errors and uncertainties. Neglecting these factors may lead to inaccurate risk assessment results, thereby compromising the correctness of safety decisions. For instance, in radiation monitoring at nuclear power plants, ignoring instrument calibration uncertainty could result either in the over-allocation of protective measures, wasting resources, or in insufficient protection, exposing personnel to radiation risks. A process industry example is the measurement of oxygen concentration in inerted vessels; uncertainty in the analyzer reading could lead to a decision that either wastes inert gas or risks creating a flammable atmosphere. By applying metrological uncertainty evaluation methods, risks can be assessed more accurately, enhancing the reliability of risk assessment and providing a more scientific basis for safety decisions.

When traditional metrological instruments, such as spectrometers and balances, are applied in the safety field, they often require adaptive modifications to meet the specific demands of safety scenarios, such as explosion-proof design, portability, and anti-interference capabilities. With continuous technological advancement, new specialized safety monitoring devices are emerging, such as trace poison sensors based on nanomaterials (e.g., graphene) and intelligent acoustic emission detectors integrated with AI algorithms [23]. The performance and accuracy of these devices are crucial for safety monitoring. Metrology plays a vital role in their development and application processes, guiding sensitivity calibration and performance verification. Through metrological methods, it is ensured that these new devices can accurately measure safety parameters, providing reliable data support for safety monitoring. For instance, the calibration of ultrasonic wall thickness

gauges used for corrosion monitoring is a direct application of metrology in process plant integrity management.

Therefore, Safety Metrology is an inevitable outcome of the expansion of traditional metrology into the safety domain. Achieving the deep integration of safety science and metrology will not only make measurement and evaluation in the safety field more scientific and accurate, promoting safety measurement towards precision, but also open up new directions for metrology itself. This integration encourages continuous innovation and refinement within metrology, expands its disciplinary boundaries, and enables it to play a more significant role in safeguarding human safety and social stability.

3.2. Social Demand Background

3.2.1. Demand for Refined Safety Management

In contemporary society, the scale of construction and operation of various major infrastructure projects continues to expand, and their safety is directly related to the national economy and people's livelihood. Major infrastructures such as bridges, high-rise buildings, and tunnels are subject to deformation over long-term use due to various factors including the natural environment and loads. These minor deformations may accumulate to a certain extent and trigger safety accidents. Therefore, millimeter-level deformation monitoring of major infrastructure has become crucial for ensuring their safe operation. The establishment of safety metrology provides a solid theoretical foundation and technical support for infrastructure safety monitoring, serving as a reliability cornerstone for currently prominent technologies such as predictive maintenance and digital twins. Traditional monitoring methods often have limited accuracy and struggle to capture minor deformation information in real-time and accurately. The establishment of Safety Metrology can introduce high-precision measurement technologies and instruments [24], such as laser interferometers and high-precision total stations, and the establishment of precise measurement benchmarks and an uncertainty evaluation system ensures the accuracy and comparability of millimeter-level deformation monitoring data. This precise measurement framework, grounded in safety metrology, not only provides high-quality data input for digital twin models—guaranteeing high consistency between the virtual model and the physical entity—but also delivers a reliable decision-making basis for predictive maintenance strategies. This enables precise safety management throughout the entire lifecycle of major infrastructure. This analogy directly applies to the monitoring of critical process infrastructure like distillation columns, reactors, and long-distance pipelines for subsidence, settlement, or stress corrosion cracking.

High-risk industries such as petrochemicals, mining, and power generation feature complex working environments, diverse risks, and potentially severe accident consequences. Risks in chemical production are difficult to assess [25], and traditional experience-based safety management struggles to accurately identify and quantify these risks. There is a need to leverage Safety Metrology to build a systematic framework, shifting safety risk assessment from qualitative to quantitative, enabling refined control of high-risk work environments, and providing reliable support for safety production decisions. The complexity of risk management in chemical production is reflected in the uncertainty of chemical reactions, leakage risks during material transportation and storage, and the difficulty in controlling equipment status under extreme operating conditions, facing multiple safety threats. Commonly used assessment methods like the Dow Index lack real-time data and accuracy. Utilizing information technology and building a risk assessment system based on Safety Metrology, deploying intelligent sensor networks combined with big data and AI algorithms, allows for real-time monitoring of key parameters and early warning, enhancing the intrinsic safety level of chemical enterprises. For example, precise measurement and

real-time analysis of reactor temperature profiles and pressure differentials can provide early warning of runaway reactions.

Occupational health protection is a vital component of safe production. In modern industry, workers face multiple occupational hazard factors. Traditional group sampling monitoring has limitations such as insufficient sample representativeness, making it difficult to accurately assess individual exposure risks [26]. Safety Metrology offers a new approach for occupational health monitoring. By equipping portable personal monitoring devices for real-time data collection and constructing personalized exposure dose assessment models combined with multi-dimensional parameters, it provides precise health protection recommendations and data support for enterprises to formulate protective measures. In the field of occupational health, the application of safety metrology similarly provides essential metrological support for the development of predictive health management and personalized protective digital twin models.

3.2.2. Multidimensional Demand for Safety Governance

The modernization of safety governance, along with technological and industrial iteration, creates an urgent demand for Safety Metrology. Currently, safety management is transitioning from “experience-driven” and “post-incident response” to “data-driven” and “pre-incident warning.” Concepts like “Industrial Internet,” “Smart Cities,” and “Digital Twins” all rely on data-driven decision-making, and Safety Metrology serves as the “quality cornerstone” ensuring that decision-making data is reliable, comparable, and traceable. Without it, advanced technologies like big data and artificial intelligence cannot function effectively. Simultaneously, technological and industrial iteration also drives the development of Safety Metrology. In the new energy sector, areas such as hydrogen leakage detection, lithium battery thermal runaway warning, and energy storage power station safety monitoring require high-precision measurement standards and traceability methods. These are directly relevant to emerging process industries like green hydrogen production and battery manufacturing. In new materials and biosafety, the measurement of nanoparticle toxicity, microplastic exposure concentration, and novel pathogen activity lacks internationally unified standards and reference materials. Safety Metrology is the prerequisite for establishing standards and conducting reliable risk assessments. In cybersecurity, the measurement of abstract concepts like “security posture,” “attack intensity,” and “system resilience” urgently requires the support of scientific metrological theories; otherwise, it is difficult to measure the effectiveness of security investments.

Further, emerging research in sustainable infrastructure development highlights the critical role Safety Metrology plays in promoting sustainability through responsible resource management. For instance, abandoned mine reuse for energy storage and geothermal systems has been identified as a sustainable solution that reduces environmental impacts while meeting energy demands. Recent studies [27] show that repurposing abandoned mines for underground energy storage, such as pumped hydro storage (UPHES) and compressed air energy storage (CAES), aligns with global sustainability goals by optimizing resource use and reducing carbon emissions. This requires rigorous Safety Metrology to ensure the safety and efficiency of these systems through reliable, traceable measurements. The integration of geothermal energy storage in such environments has proven to be a viable method for reducing the carbon footprint of the energy sector and promoting long-term energy sustainability [28].

Regulatory alignment with international standards and accident investigation and liability determination also highlight the importance of Safety Metrology. With the deepening of global trade and technical cooperation, the internationalization of safety standards is an inevitable trend. For instance, safety performance test data for equipment manufactured in

China and entering the EU market needs recognition by EU regulatory authorities. The core of this mutual recognition is the equivalence of measurement results, which relies on a safety metrology system. Furthermore, in post-accident investigations, the precise measurement and reconstruction of key parameters such as explosion equivalent, structural failure stress, and chemical leakage volume are crucial for clarifying responsibility and improving design. These measurement results, serving as judicial evidence, must possess indisputable metrological traceability. The investigation of process industry accidents (e.g., vapor cloud explosions) heavily depends on such traceable forensic metrology.

3.2.3. Contribution to Sustainable Risk Governance

Safety Metrology provides a foundational framework for achieving sustainable risk management in high-hazard industries. By enabling precise, comparable, and traceable safety data, it supports: (1) the optimization of maintenance resources and energy consumption through predictive algorithms, reducing environmental footprints; (2) enhanced system resilience and adaptability to emerging risks, aligning with the United Nations Sustainable Development Goals (SDGs), particularly Goals 9 (Industry, Innovation, and Infrastructure) and Goals 11 (Sustainable Cities and Communities); and (3) improved compliance with evolving environmental, social, and governance (ESG) criteria. Through these mechanisms, Safety Metrology facilitates a holistic approach to safety that integrates operational integrity, environmental protection, and long-term socio-economic sustainability.

3.2.4. Demand for Intelligent Safety Decision-Making

The construction of smart cities is a current urban development trend, and the Smart City Security Operation Center (SOC) is the core for ensuring the safe operation of smart cities. Smart cities involve numerous domains and systems, such as transportation, energy, and communications, which generate vast amounts of multi-source data. However, due to the different sources and varied formats of these data, effective sharing and integration become challenging. The establishment of Safety Metrology can provide standardized multi-source data access solutions for the Smart City SOC. By formulating unified data standards and interface specifications, data from different sources and formats can be processed standardized, enabling effective integration and analysis within the SOC. This not only improves data utilization efficiency but also provides more comprehensive and accurate information support for safety decision-making in smart cities [29]. The analogous need exists in ‘Smart Plants’ or integrated operations centers (IOCs) for process industries, where data from various subsystems (DCS, SIS, vibration monitoring, corrosion monitoring) must be integrated on a common, reliable metrological basis for holistic safety oversight.

Risk quantification models are important tools for intelligent safety decision-making. Smart cities face various complex safety risks, such as natural disasters and public security incidents. To assess these risks promptly and accurately, risk quantification models need to be established. For example, Bayesian Networks are a commonly used risk quantification model. By modeling the causal relationships between various risk factors, they can effectively handle uncertain information and achieve quantitative risk assessment. However, a crucial premise must be recognized: without the standardized measurement systems and data quality assurance mechanisms provided by safety metrology, even the most advanced algorithmic models will be constrained by the fundamental principle that “the quality of input data determines the reliability of output results.” The establishment of Safety Metrology can further refine risk quantification models. By making measurement data more precise and data analysis methods more advanced, risk quantification models can be made more accurate and reliable. Optimizing and improving risk quantification

models based on practical application scenarios allows them to better adapt to the safety decision-making needs of smart cities.

Resource optimization algorithms are the core technical support for realizing intelligent safety decision-making. Within the smart city safety management system, a significant contradiction exists between the finiteness of safety resources and the comprehensiveness of risk prevention and control. How to achieve optimal resource allocation becomes a key issue for urban safety operations. The systematic construction of Safety Metrology provides a new technical path to solve this problem. By establishing a precise metrological monitoring network, multi-dimensional evaluation of the usage effectiveness of various safety resources can be achieved, including key indicators such as resource distribution density, response timeliness, and coverage range. Based on the dynamic assessment results output by risk quantification models, combined with machine learning optimization algorithms, intelligent scheduling and dynamic allocation of safety resources can be realized. It must be emphasized that the effectiveness of these intelligent algorithms is entirely dependent on the quality of the input data. Safety metrology serves as the fundamental guarantee for ensuring data reliability, thereby preventing decision-making deviations caused by data quality issues. Taking emergency response to natural disasters as an example, by monitoring risk level changes in different regions in real time, the system can automatically generate optimal resource deployment plans, ensuring that key resources like rescue forces and material equipment are precisely allocated to high-risk areas, significantly improving emergency response efficiency and minimizing disaster losses. In a process plant context, this translates to the optimal allocation of maintenance resources (inspectors, technicians) based on real-time risk rankings derived from metrologically sound integrity monitoring data.

The theoretical construction and technical application of Safety Metrology represent the development direction of modern safety management. This emerging discipline provides innovative solutions for key areas such as health monitoring of major infrastructure, dynamic risk assessment of chemical processes, precise occupational health protection, and safety operations of smart cities by establishing standardized measurement systems and data analysis methods. As the cornerstone of data-driven safety management, safety metrology fundamentally addresses critical issues such as “unclear data traceability and undefined measurement uncertainty” that compromise algorithmic reliability, thereby providing quality assurance for the effective application of big data and artificial intelligence technologies in the safety domain. Its core value lies in realizing the transition from empirical judgment to data-driven approaches, from qualitative analysis to quantitative assessment, and from passive response to active prevention. With the deep integration of new-generation information technologies like the Internet of Things, big data, and artificial intelligence, Safety Metrology will continue to drive innovation in safety management models, providing powerful technical support and theoretical guarantee for building a safe, resilient, and sustainable social development environment.

4. Theoretical Foundations of Safety Metrology

4.1. Philosophical Foundations

4.1.1. Measurement Ontology

(1) The Objective Measurability of Safety States

The safety state, as a key research object of Safety Metrology, possesses objective measurability [30], which serves as a crucial philosophical cornerstone for constructing this discipline. In essence, the safety state is an objective attribute manifested by a system under specific environments and conditions. Whether it is a production workshop, a bridge, or an urban safety operation system, its safety state is influenced by numerous factors such

as the physical environment, equipment performance, and human behavior, and these influencing factors can be observed, detected, and quantified.

Taking a chemical workshop as an example, its safety state can be assessed by measuring physical parameters such as temperature, pressure, and concentration of hazardous gases. These parameters exist objectively and can be precisely determined using various measurement instruments and technologies. By monitoring and analyzing these parameters in real time, the safety status of the chemical workshop can be accurately grasped. The same applies to the transportation field, where the safety state of traffic can be objectively assessed by measuring and analyzing factors such as road conditions, vehicle speed, and driver behavior. Evidently, the objective measurability of safety states provides the material support for the construction of Safety Metrology.

(2) The Possibility of Quantitative Representation of Safety Risks

Safety risk is a key concept in the safety domain, reflecting the potential dangers and losses a system may face in the future. Although safety risk involves a degree of uncertainty, it is not unquantifiable. In fact, by analyzing large amounts of historical data, it can be found that the occurrence of safety risks follows certain patterns and probability distributions.

Drawing an analogy from risk assessment work in the financial sector, financial institutions quantify investment risks by analyzing market data, corporate financial data, etc., and applying risk assessment models. A similar approach can be adopted in the safety field. By statistically analyzing accident cases and risk factors, safety risk assessment models can be established for quantitative representation. For instance, in construction, by analyzing past construction accidents, the probability of risk and the degree of loss under different construction phases and conditions can be determined. By evaluating various factors of the current construction project and using the model, a safety risk value can be calculated. This quantitative representation helps in intuitively understanding the magnitude of risk and provides a scientific basis for safety decision-making. In the process industries, this is exemplified by quantitative risk assessment (QRA) models that calculate individual risk contours and potential loss of life (PLL) based on equipment failure rate data, meteorological conditions, and population density. The reliability of these models depends fundamentally on the quality of the input measurement data.

4.1.2. Cognitive Methodology

(1) The Paradigm Shift from “Empirical Perception” to “Data Cognition”

From the perspective of cognitive methodology [31], this paradigm shift is closely related to the philosophical foundation of Safety Metrology, which emphasizes the measurability of safety states and the quantification of risk. “Data cognition,” developed based on this foundation, quantifies safety states and risks through the collection and analysis of data, providing accurate and objective evidence for safety management, embodying the transition from “empirical perception” to scientific rational cognition.

This shift is highly significant for the construction of Safety Metrology. It provides data resources and analytical tools; vast amounts of safety data lay the foundation for measurement and assessment. Analyzing data can help determine the range of safety indicators and establish metrological models. For example, traffic accident data can contribute to the development of traffic safety metrology. Data analysis techniques can uncover safety patterns, improve measurement accuracy, and verify and optimize results, thereby refining theoretical methods. This shift is an inevitable development in safety management, providing support for Safety Metrology and enabling it to operate more scientifically and accurately.

(2) The Relationship between Measurement Uncertainty and Safety Decision Confidence

In Safety Metrology, measurement uncertainty, influenced by factors such as instrument precision, environmental variations, and methodological limitations, reflects the reliability of the results and is closely linked to safety decision confidence. Safety decision confidence refers to the decision-maker's trust in the reliability and validity of the decision. When making decisions, the impact of measurement uncertainty must be considered. High measurement uncertainty affects decision confidence. For example, in a chemical enterprise measuring hazardous gas concentration, if the uncertainty is high, it becomes difficult to determine whether the actual concentration truly exceeds the safe limit, thereby affecting the confidence in decisions regarding the activation of protective measures or evacuation orders.

To enhance decision confidence, measures can be taken to reduce uncertainty, such as selecting high-precision instruments, optimizing measurement methods, and controlling environmental conditions. Furthermore, it is essential to evaluate and analyze the uncertainty and incorporate it into the decision-making consideration process. When determining acceptable risk levels, decision-makers must account for the range of measurement uncertainty. A larger measurement uncertainty implies that even if the nominal risk value falls within an acceptable range, the actual risk may exceed expectations. Conversely, a smaller measurement uncertainty provides more precise risk boundaries, thereby offering a reliable basis for establishing scientifically sound acceptable risk levels. This is critically important in process safety for decisions such as setting alarm setpoints, determining safety instrumented system (SIS) trip settings, and defining safe operating limits (SOLs).

The philosophical foundation of Safety Metrology is rooted in the theory of safety measurability. This theory establishes, at the level of measurement ontology, the core cognition that "the safety state has a quantifiable nature." From the perspective of cognitive methodology, it provides the logical path for "transforming abstract risks into measurable parameters," offering fundamental support for the disciplinary construction of Safety Metrology. This theory not only facilitates the paradigm shift in safety management from "experience-driven" to "data-driven" but also, by clarifying core relationships such as "qualitative description vs. quantitative measurement" and "static assessment vs. dynamic perception," provides philosophical guidance for the theoretical deepening and practical expansion of Safety Metrology, ultimately promoting the leap of safety management levels towards precision and scientificity.

4.2. *Disciplinary Theoretical Foundations*

4.2.1. Safety Science Theory

Safety Science Theory [32] serves as the crucial theoretical cornerstone for the construction of Safety Metrology, establishing its fundamental framework [16,33] and providing principles and methods. Safety Science Theory aims to explore how to effectively prevent, control, and eliminate various hazardous factors in human production, daily life, and other activities to avoid accidents and protect human life, property, and environmental safety.

Safety Science Theory includes fundamental principles such as the System Principle, Prevention Principle, and Enforcement Principle. The System Principle treats safety issues as a systemic engineering problem, comprehensively considering the interrelationships among elements like humans, equipment, environment, and management, requiring a holistic and in-depth analysis of the safety system to grasp the problem overall. The Prevention Principle emphasizes focusing efforts on preventing accidents before they occur, establishing the concept of "Safety First, Prevention Foremost," and proactively identifying and assessing potential hazards for preemptive prevention. The Enforcement Principle requires the state and enterprises to formulate mandatory safety regulations, standards, and systems to ensure the effective implementation of safety work, regulate

people's behavior, and enhance safety awareness and levels across society. Safety Metrology supports the implementation of mandatory principles through standardized measurement methods. It establishes unified safety metrology standards and specifications, provides a scientific basis for the formulation of regulations and standards, and verifies compliance through traceable measurement results, thereby ensuring the effective implementation of mandatory requirements.

Safety Science Theory is highly significant for Safety Metrology. It provides the theoretical basis for Safety Metrology. When conducting quantitative analysis of safety phenomena and processes, this theory is needed to determine the objects, scope, and methods of measurement; Safety Metrology provides technical support for safety science theories to transition from qualitative description to quantitative analysis by converting key elements of various safety theories into measurable parameters, thereby realizing the scientification and precision of safety management. It guides the determination of indicators. Based on different research contents, a series of safety metrology indicators can be determined to accurately reflect the safety status; for instance, corresponding indicators are determined according to Human Factors Safety Theory and Equipment Safety Theory, respectively. It also promotes the development of Safety Metrology methods. As Safety Science Theory continuously innovates, it provides more scientific and accurate measurement methods for Safety Metrology; for example, analysis methods and assessment models based on accident causation theory and risk theory make safety measurement more accurate and reliable. For process safety, this translates into developing metrics for human reliability in control room operations (Human Factors), for pressure vessel integrity (Equipment), for area classification (Environment), and for the effectiveness of process safety management system audits (Management).

4.2.2. Metrology Theory

The definition of Metrology originates from the International Vocabulary of Metrology (VIM), first systematically defined in 1984, with the latest version being VIM3 [34]. Its foundational system is constructed by the International System of Units (SI), established by the Metre Convention in 1875 and the measurement theory laid down by Newton. The term "Metrology" was introduced in China in 1953 and defined as the "science of measurement" in national standards, thereby establishing the conceptual foundation of metrology in the country.

Metrology is a vital theoretical root for Safety Metrology, providing core support for quantitative analysis and accurate assessment in the safety field. It mainly involves several aspects: Basic Metrological Concepts and Principles [35], Measurement Methods and Techniques, Measuring Instruments and Reference Materials, and Metrological Management and Regulations. The deep integration and innovative application of its core conceptual framework are pivotal to constructing safety metrology. Safety metrology not only adopts the technical methods of metrology but, more importantly, systematically introduces the philosophical principles and methodological systems of metrology into the field of safety.

Safety Metrology extends the principles of the International System of Units (SI) into the safety domain by establishing a unified framework for safety measurement [36]. It defines standardized units like safety equivalents and risk index units, ensuring consistency across industries in both quantitative values and measurement methodologies. Moving beyond traditional single-parameter measurements, Safety Metrology integrates multi-source data fusion to assess overall system safety, incorporating data from personnel behavior, equipment status, and environmental parameters into a composite safety index. Additionally, it expands the scope of measurement instruments to include behavioral sensing devices, ensuring the reliability and accuracy of safety data through careful instrument selection

and calibration using reference materials. The introduction of a Metrological Management System ensures that measurement data is traceable, scientifically valid, and supports safety governance. This transformation elevates safety management from experience-based to science-based approaches, representing a theoretical innovation that deepens the integration of metrology and safety science, thus improving safety decision-making and regulatory compliance across industries.

In the construction of Safety Metrology, Basic Concepts and Principles lay the theoretical foundation for quantitative analysis and assessment, ensuring accurate and consistent measurement results. Measurement Methods and Techniques provide diverse means for obtaining safety parameters, adapting to different monitoring needs. Measuring Instruments and Reference Materials, as core tools and carriers of quantity values, directly determine the reliability of safety metrology data through their accuracy, stability, and standardization. Metrological Management and Regulations, through institutional constraints and legal safeguards, standardize the entire process of metrological activities, maintaining the legality, scientificity, and sustainability of safety metrology work. These four components together form the complete framework of Safety Metrology, each being indispensable, as illustrated in Figure 2.

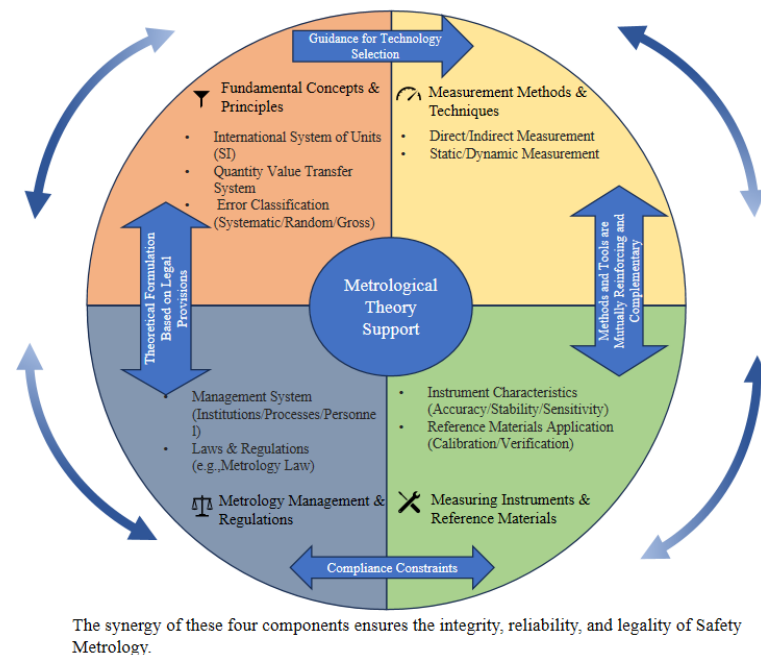


Figure 2. The Role of Basic Metrology in Safety Metrology.

4.2.3. Theories Underpinning the Establishment of Interdisciplinary Fields

Currently, with the continuous deepening of scientific research and the increasingly diverse demands of social development, the importance of interdisciplinary fields is becoming more prominent in both academia and practical domains. As an interdisciplinary field, the establishment of Safety Metrology relies on the relevant theoretical foundations for creating such disciplines. The formation of an interdisciplinary field is the result of the deep integration of knowledge from different disciplines [37]. Traditional Safety Science theory and Metrology theory possess their own independent knowledge systems and research methods. To construct Safety Metrology, it is necessary to break down disciplinary boundaries and achieve a deep integration of their knowledge. Safety Science is dedicated to preventing and controlling various safety accidents, protecting personnel, property, and the environment. Its knowledge system encompasses safety principles, safety management, risk assessment, and more. Metrology focuses on the precise measurement

and calibration of various physical, chemical, and other quantities, ensuring reliable and consistent measurement results. In Safety Metrology, metrological measurement techniques are introduced to meet the need for risk quantification in Safety Science. For instance, during safety risk assessment, metrological methods are used to precisely measure and analyze various risk factors, providing a scientific basis for safety decision-making. This knowledge integration is not a simple patchwork; it requires the organic combination of knowledge elements from different disciplines, facilitated by constructing knowledge classification systems, such as the method advocated by the “Knowledge Block Matrix.” In Safety Metrology, based on the different types of safety problems and metrological needs, knowledge from Safety Science and Metrology can be divided into different “knowledge blocks.” These blocks are then combined and interrelated in a matrix fashion to form a complete knowledge system. A key knowledge block for process safety is the integration of ‘hazardous material properties (Safety Science)’ with ‘advanced analytical chemistry measurement techniques (Metrology)’.

The establishment of a discipline often originates from the intersections and blank areas between existing disciplines, as these areas are the growth points for new disciplines [38]. The establishment of Safety Metrology also has multiple growth points. On one hand, with technological advancement, new safety issues continuously emerge, such as those in cybersecurity and biosafety. The safety issues in these fields possess unique natures and characteristics, making it difficult for traditional Safety Science theory and Metrology theory to meet the research and practical needs. Therefore, at the intersection of these emerging safety fields and Metrology, new growth points for Safety Metrology are formed. For example, the cybersecurity field requires accurate measurement and assessment of network attack intensity, frequency, impact scope, etc., which necessitates introducing metrological methods into cybersecurity research, promoting the development of Safety Metrology in this domain. On the other hand, research methods and techniques from different disciplines can be mutually borrowed and transplanted, generating new research ideas and methods. In Safety Metrology, one can draw upon metrological uncertainty analysis to assess the reliability of safety results; conversely, applying the systematic analysis methods of Safety Science to metrological measurement processes can improve measurement accuracy and stability. This cross-fertilization and integration of research methods and techniques provide new impetus and direction for the development of Safety Metrology. For instance, applying the concept of ‘safety barriers’ from safety science to the design of measurement traceability chains can enhance the overall robustness of the measurement system against failures or tampering.

The development of interdisciplinary fields relies on collaboration between different disciplines, which is also an important theoretical foundation for their establishment. In the process of establishing and developing Safety Metrology, close cooperation among Safety Science, Metrology, and other related disciplines is necessary to form a cohesive whole. Researchers from different disciplines should strengthen communication and collaboration to jointly explore research problems and development directions in Safety Metrology. Experts in the Safety Science field can provide practical needs and research backgrounds related to safety issues, while experts in Metrology can provide professional measurement techniques and methods. Collaboration between both sides can better solve practical problems in Safety Metrology. The sharing and integration of resources between disciplines is also crucial. In research and practice, it is necessary to share resources such as safety data, measurement equipment, and research findings to improve resource utilization efficiency. Furthermore, strengthening interdisciplinary talent cultivation and exchange is essential, fostering composite talents proficient in both Safety Science and Metrology, thereby providing human resource guarantees for the development of Safety Metrology.

This is crucial for addressing complex process safety challenges that require both deep process knowledge and metrological rigor.

The theoretical foundations for establishing interdisciplinary fields provide important guidance and support for the construction of Safety Metrology. Through knowledge integration, exploration of new growth points, and realization of interdisciplinary development, Safety Metrology can better meet the modern society's demands for safety measurement and assessment, contributing to the ensuring the safe and stable development of society. The cross-recombination of knowledge generates new disciplines that transcend the boundaries of their original fields. A prime example is the intersection of metrology's "uncertainty analysis" and safety science's "accident causation theory." This fusion has given rise to methodologies for assessing the credibility of accident investigations—systematically integrating metrological uncertainty evaluation techniques throughout the entire investigative process. By establishing an evidence credibility rating system, developing uncertainty analysis models for causal factor weighting, and creating holistic credibility evaluation metrics for investigation reports, it provides an objective, scientifically grounded basis for accident liability determination rooted in measurement data. Another illustration lies in the combination of metrology's "metrological traceability techniques" with safety science's "risk evolution patterns," which has led to the development of risk propagation traceability models. Drawing upon metrology's concept of value transmission, these models construct a reverse-traceability mechanism from risk consequences back to risk sources, ensuring data accuracy and consistency across all stages of risk evolution. Such theoretical collisions not only achieve organic integration of disciplinary knowledge but, more significantly, catalyze the emergence of practically applicable new concepts, methodologies, and technologies through the cross-recombination of knowledge modules. This continuous interdisciplinary synergy provides sustained momentum for the innovative development of safety metrology. Based on the analysis of Safety Metrology in terms of knowledge integration, growth point exploration, and disciplinary development, Figure 3 more intuitively and clearly illustrates the relationships between Safety Metrology and related disciplines.

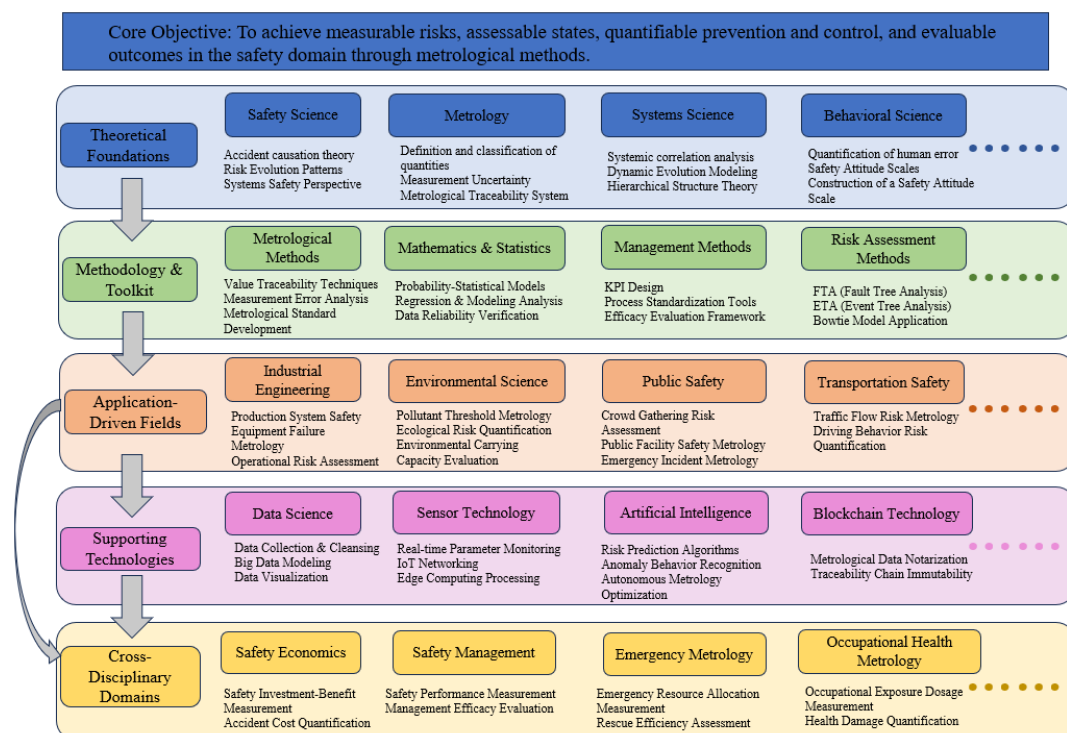


Figure 3. Logical Relationship Diagram of Safety Metrology and Related Disciplines.

5. Discussion

This section highlights the limitations of the proposed framework and explores potential future research directions, focusing on the need for validation through case studies, the development of standardized Safety Metrology systems, and further refinement of interdisciplinary integration and theoretical components. Additionally, it outlines the significant managerial and practical implications of Safety Metrology, emphasizing its potential to improve safety decision-making, enhance regulatory practices, and provide real-time, data-driven safety management in process safety engineering.

(1) Research Limitations and Future Directions

As a conceptual and theoretical exploration, this study has several limitations that point to important avenues for future research. The proposed framework requires validation through case studies in specific process industries (e.g., refining, petrochemicals, pharmaceuticals) and empirical analyses to demonstrate its practical applicability and effectiveness. Moreover, the development of a standardized system for Safety Metrology will be a long-term endeavor, demanding sustained collaboration across disciplines and institutions. Future work should also focus on refining the disciplinary boundaries, theoretical components, and implementation mechanisms of Safety Metrology to ensure its relevance and adaptability across diverse application contexts. Specific future research for process industries includes: developing standard methods for measuring safety barrier effectiveness (e.g., SIL verification), creating reference datasets for equipment failure rates under specific process conditions, and establishing metrological protocols for emerging risks like hydrogen embrittlement or nanoparticle exposure.

(2) Managerial and Practical Implications

Safety Metrology offers significant value for both organizational management and regulatory practices. For enterprises, particularly in the process industries, it provides a theoretical basis for developing quantifiable safety performance indicators, facilitating the transition from experience-based to data-driven safety management and enabling more precise loss prevention through predictive maintenance and dynamic risk assessment. For government regulators, it supports the formulation of scientific, equitable safety standards and regulations, thereby enhancing the objectivity and credibility of oversight in areas such as accident investigation, liability assessment, and compliance monitoring. It provides a sound scientific basis for enforcing process safety management (PSM) regulations and benchmarking industry performance.

(3) Practical Value of Safety Metrology in Process Safety Engineering

In process safety engineering, Safety Metrology provides practical value by enabling accurate, real-time measurements that directly inform safety decisions. For example, in high-risk environments like chemical plants, Safety Metrology can standardize the measurement of key safety parameters such as pressure, temperature, and corrosion rates, which are critical for maintaining safe operational conditions. This allows for continuous monitoring and immediate response to deviations, ensuring that safety measures are always aligned with real-time risks. Furthermore, the integration of multi-source data from equipment sensors, environmental factors, and human behavior into a unified safety index offers a more holistic view of system performance, helping engineers identify emerging risks before they escalate into catastrophic events. By quantifying safety performance through standardized methods, Safety Metrology also improves the precision of risk assessments and helps organizations meet regulatory requirements more effectively. This increased accuracy and reliability in decision-making enhances the overall safety culture in process

industries, reducing accidents, operational downtime, and financial losses while ensuring compliance with industry standards.

6. Conclusions

This paper systematically establishes the theoretical positioning of Safety Metrology as an interdisciplinary field bridging Safety Science and Metrology, defining its core mission to address fundamental challenges in safety quantification—specifically, establishing benchmarks, ensuring consistency, and guaranteeing reliability—to enable accurate quantification of safety states and robust risk-informed decision-making. The emergence of Safety Metrology is driven by a dual impetus: internally, by the shift of Safety Science toward a data-driven paradigm, and externally, by pressing societal needs such as monitoring critical infrastructure and assessing risks in chemical processes. A four-dimensional theoretical framework—integrating philosophical foundations, principles of Safety Science, fundamentals of Metrology, and interdisciplinary theories—has been constructed, providing a robust, cross-disciplinary foundation for the establishment of this emerging field.

Safety Metrology represents more than a collection of technical tools—it is a transformative force driving the evolution of safety culture and governance toward greater scientific rigor and precision and sustainable risk resilience. By enabling a shift from qualitative judgment to quantitative analysis and from reactive measures to proactive risk management, it holds the potential to fundamentally improve the predictability and controllability of safety risks while supporting sustainable industrial development. The maturation of Safety Metrology will not only advance the discipline of Safety Science but also contribute meaningfully to the modernization of safety governance systems worldwide and the integration of safety, sustainability, and resilience in high-hazard sectors. For the Process Industries, the adoption of safety metrology principles promises a future where process risks are not just managed, but measured, benchmarked, and controlled with an unprecedented degree of precision, directly contributing to the reduction of major accidents and economic losses and promoting safer, more sustainable operations.

Looking ahead, as Safety Metrology continues to mature, it will not only advance the discipline of Safety Science but also significantly contribute to the modernization of global safety governance systems. Its integration with emerging technologies and its focus on data-driven decision-making will strengthen the scientific rigor and reliability of safety management across high-risk sectors, providing a foundation for long-term safety and sustainability. Furthermore, Safety Metrology will play a key role in achieving sustainability outcomes by reducing accident-related environmental releases, as it facilitates the identification of potential hazards and the implementation of proactive safety measures that minimize the risk of environmental damage. This integration of sustainability into safety management practices will help industries not only meet regulatory requirements but also contribute to environmental protection and sustainable operations.

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References

1. Qiu, K. Discussion and Case Analysis on the Construction of Dual Prevention Mechanism in Chemical Enterprises. *Shandong Chem. Ind.* **2023**, *52*, 229–232.
2. Yang, T. Problems and Countermeasures of Dual Prevention Mechanism of Risk Hierarchical Control and Hidden Danger Investigation and Treatment in Petrochemical Industry. *Mod. Chem. Res.* **2022**, *3*, 23–25.
3. ISO 31000; Risk Management—Guidelines. ISO: Geneva, Switzerland, 2018.
4. UNDRR. GAR Special Report 2023: Mapping Resilience for the Sustainable Development Goals. Retrieved 10 July 2025. Available online: <https://www.undrr.org/gar/gar2023-special-report> (accessed on 7 January 2026).
5. Garvey, P.R.; Lansdowne, Z.F. Risk Matrix: An Approach for Identifying, Assessing, and Ranking Program Risk. *Air Force J. Logist.* **1998**, *22*, 16–23.
6. Editorial Board. Metrology for Safety. *Chem. Int.* **2012**, *34*, 20. [CrossRef]
7. Isigonis, P.; Bouman, E.A.; Varsou, D.D.; Jensen, K.A.; Fransman, W.; Drobne, D.; Rollon, B.P.; Ballesteros, A.; Rodríguez-Llopis, I.; Säämänen, A.; et al. A Nano Risk Governance Portal Supporting Risk Governance of Nanomaterials and Nano-Enabled Products. *Comput. Struct. Biotechnol. J.* **2025**, *29*, 177–185. [CrossRef]
8. Fu, S.; Niu, S.Q.; Lai, Z.B.; Guo, X.Y. Risk Analysis of Civil Aircraft Fire Accidents Based on FTA and BN. *J. Zhengzhou Univ. Aeronaut.* **2024**, *42*, 47–53.
9. Xu, Y.M.; Tian, M.Y.; Li, Z.; Chen, W.T.; Lv, W. Analysis of Influencing Factors of Airport Runway Incursion Accident Based on FTA-BN. *J. Saf. Environ.* **2023**, *23*, 1361–1367.
10. Aven, T.; Zio, E. Some considerations on the treatment of uncertainties in risk assessment for practical decision making. *Reliab. Eng. Syst. Saf.* **2014**, *125*, 67–75. [CrossRef]
11. NIST SP 800-82; Guide to Operational Technology (OT) Security. NIST: Gaithersburg, MD, USA, 2023.
12. Hollnagel, E. *Safety-I and Safety-II: The Past and Future of Safety Management*; CRC Press: Boca Raton, FL, USA, 2014.
13. Hale, A.; Hovden, J. Management and Culture: The Third Age of Safety. A Review of Approaches to Organizational Aspects of Safety, Health and Environment. In *Occupational Injury: Risk, Prevention and Intervention*; CRC Press: Boca Raton, FL, USA, 1998; Volume 28, pp. 1–14.
14. Brown, R.J.C. Measuring measurement—What is metrology and why does it matter? *Measurement* **2021**, *168*, 108408. [CrossRef]
15. Wang, B.; Wu, C. Study on the Background and Foundation for the Establishment of Safety & Security-Related Intelligence Science. *J. Intell.* **2018**, *37*, 28–36.
16. Wu, C. Research on Theory of Developing Safety Science Discipline. *Saf. Secur.* **2019**, *40*, 1–6+81.
17. Wang, W.C.; Chen, S.Y.; Zhang, X.D.; Lai, X.; Sun, J.Q. Low-Altitude Flight Safety Risk Analysis and System Management. *Adv. Aeronaut. Sci. Eng.* **2025**. online First.
18. Yang, Y.; Zhang, W.B.; Zuo, C.X.; Wang, Z.X. Evolution Analysis of Digital Mine Safety Management Based on “Man-Machine-Environment-Management” Theory. *Saf. Coal Mines* **2021**, *51*, 239–243, 247.
19. Guo, P.; Wang, M.; Dang, G.; Zhu, T.; Wang, J.; He, M. Evaluation method of underground water storage space and thermal reservoir model in abandoned mine. *Rock Mech. Bull.* **2023**, *2*, 100044. [CrossRef]
20. Liu, M.; Sun, Y. Review of Elementary Constants in International System of Units. *J. Electron. Meas. Instrum.* **2021**, *35*, 1–9.
21. Zhi, S.P. Values Define the World, Precision Changes the Future. *China Quality Daily*, 20 May 2016. p. 001.
22. Ye, D.P.; Huang, G.L. Introduction to the Revision of GUM and VIM by the Joint Committee for Guides in Metrology. *China Metrol.* **2008**, *1*, 89–92.
23. Fang, L.D.; Xu, X.X.; Ma, X.Y.; Wang, S.; Li, X.T.; Wei, Z.H. Discussion on Remote Transfer and Traceability of Quantity Values Technology of Measuring Instruments. *China Meas. Test* **2021**, *47*, 1–8+35.
24. Yang, H.X.; Fu, H.J.; Hu, P.C.; Yang, R.T.; Xing, X.; Yu, L.; Chang, D.; Tan, J.B. Ultra-Precision and High-Speed Laser Interferometric Displacement Measurement Technology and Instrument. *Laser Optoelectron. Prog.* **2022**, *59*, 305–319.
25. Meng, F.Z.; Sun, B.; Yang, Z. Impact and Risk Assessment of Feedstock Substitution on New Process Safety in Chemical Production. *Chem. Ind. Eng. Prog.* **2025**, *44*, 2955–2971.
26. Xiang, X.X.; Zhang, X.J.; Liu, Y.; He, L.; Luo, J. Monitoring and Occupational Health Risk Assessment of Key Volatile Organic Compounds in Work Place Air Based on Qualitative Monitoring. *J. Environ. Occup. Med.* **2024**, *41*, 1246–1250.
27. Menéndez, J.; Ordóñez, A.; Álvarez, R.; Loredó, J. Energy from closed mines: Underground energy storage and geothermal generation. *Appl. Energy* **2019**, *108*, 498–512.

28. Cui, C. Planning for the reuse of abandoned mines: Sustainable development and value evaluation. *Processes* **2025**, *13*, 3894. [[CrossRef](#)]
29. Gong, J.Y.; Zhang, X.; Xiang, L.G.; Chen, N.C. Progress and Applications for Integrated Sensing and Intelligent Decision in Smart City. *Acta Geod. Cartogr. Sin.* **2019**, *48*, 1482–1497.
30. Guo, G.C.; Xiao, X.J. Measurement Realism. *Sci. Technol. Dialectics* **1996**, *5*, 23–28.
31. Wang, H.S. The Cognitive Methodology of Scientific Imagination. *J. Dalian Univ. Technol.* **1992**, *4*, 476–482.
32. Wu, C. Idea Models for Research on Basic Theory of Safety & Security Science and Its Popularization and Application. *Saf. Secur.* **2021**, *42*, 29–34.
33. Wu, C.; Yang, M. Study of Safety Science Principles and Their Constructions. *China Saf. Sci. J.* **2012**, *22*, 3–10.
34. *ISO/IEC Guide 99-2007*; International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM). International Organization for Standardization: Geneva, Switzerland, 2007.
35. Qiu, J.P.; Xu, Z.Y. Disciplinary Construction and Development Trend of Datametrics. *Adv. Inf. Sci.* **2022**, *45*, 27–36.
36. Yang, P. The Value of Metrological Management in the Construction of Quality Management System. *China Qual. Superv.* **2025**, *2*, 74–75.
37. Wu, C. Construction of Interdisciplinary Knowledge Classification System by Using Science Chunk Matrix. *Technol. Innov. Manag.* **2021**, *42*, 470–476.
38. Wu, C. Research on the Basic Theory of Science of New Disciplines. *Technol. Innov. Manag.* **2022**, *43*, 342–350.

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