Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume I, 209-214

Condition Based and Risk Oriented Lifecycle Safety Management of Conventional Ammunition Using Non-Destructive Diagnostic Data

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***Abstract*—The paper develops an expanded condition-based and risk-oriented framework for lifecycle safety management of conventional ammunition using non-destructive diagnostic data as the main source of technical evidence. The study has three focused objectives: to convert diagnostic observations into comparable condition indicators, to map degradation-related evidence to risk-oriented safety categories, and to connect those categories with documented lifecycle management actions. The proposed framework addresses practical challenges associated with ageing stockpiles, heterogeneous storage environments, incomplete historical records, and limited inspection resources. It combines five connected functions: diagnostic data acquisition, extraction and normalization of condition indicators, interpretation of degradation-related evidence, risk-oriented safety categorization, and selection of lifecycle management actions with feedback-driven reassessment. The key finding is that non-destructive diagnostics become most useful for ammunition safety governance when they are embedded in an auditable decision logic rather than treated as isolated inspection outputs. The practical implication is improved traceability of decisions related to continued storage, intensified surveillance, handling restrictions, maintenance planning, segregation, or withdrawal from service. The main scientific contribution is a transferable methodology that links diagnostic evidence, evidential confidence, risk categorization, and lifecycle action in a structured form suitable for progressive digital integration.**

Keywords—condition based assessment, conventional ammunition, lifecycle safety management, non-destructive diagnostics.

I. Introduction

The long term storage and management of conventional ammunition require a balanced approach that simultaneously addresses safety assurance, technical uncertainty, and operational effectiveness. International practice increasingly treats ammunition management as a through life activity extending from manufacture and transfer to storage, surveillance, transport, use, recovery, and disposal [1], [6], [8], [9]. Within that perspective, stockpile safety cannot rely only on nominal service life or on periodic administrative categorization. Ammunition items age under variable environmental and handling conditions, and the quality of historical records often differs across facilities and batches. These realities create a strong need for evidence based assessment methods that can support auditable decisions on continued storage, increased monitoring, handling restrictions, or withdrawal from service [3], [4], [6], [7].

The research objective is to formulate a structured and auditable framework for lifecycle safety management of conventional ammunition based on non-destructive diagnostic data and risk-oriented evaluation logic. More specifically, the study aims to: define a five-stage workflow that converts diagnostic observations into condition indicators; establish an interpretation logic that links degradation evidence, severity, safety relevance, and evidential confidence; map the interpreted evidence to practical safety categories; and connect these categories with lifecycle management actions, including continued storage, intensified surveillance, restricted handling, segregation, maintenance-oriented intervention, or withdrawal from service. In this way, the study seeks to strengthen the traceability of ammunition safety decisions under conditions of ageing stockpiles, heterogeneous records, and limited inspection resources.

The remainder of the paper is organized as follows. Section II outlines the lifecycle safety context, the

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol1.147

methodological assumptions of the proposed framework, and the role of non-destructive diagnostics in ammunition management. Section III presents the interpretation logic for diagnostic indicators and discusses how indicator evidence can be mapped to risk categories. Section IV extends the discussion toward practical applicability, prioritization, traceability, and implementation constraints. The final section summarizes the main findings and indicates directions for future development of condition based ammunition safety management.

II. MATERIALS AND METHODS

Lifecycle safety management of conventional ammunition must address a complex combination of technical, organizational, and operational factors. The International Ammunition Technical Guidelines and related United Nations publications consistently emphasize that risk reduction in ammunition management depends on surveillance, suitable storage conditions, documented procedures, and coherent disposal planning [1]–[6]. In parallel, the life cycle management literature argues that stockpile safety and sustainability depend on linking planning, stockpile management, and disposal as parts of one integrated system rather than treating them as isolated administrative tasks [7], [8]. These observations are directly relevant to military depots and security institutions that must preserve readiness while minimizing the probability and consequences of undesirable explosive events.

Within this context, non-destructive diagnostic methods provide an important basis for condition aware safety management. Their value lies not only in detecting visible or latent signs of degradation, but also in enabling technical assessment without compromising the usability or safety of the inspected item. Reviews of non-destructive evaluation and condition monitoring show that multi modal inspection, sensor based observation, and structured indicator extraction are increasingly used to support predictive maintenance and safety management in complex engineering systems [10]–[13]. The proposed framework adapts these general ideas to ammunition lifecycle safety management by treating diagnostic data as decision enabling evidence rather than as standalone inspection output.

The proposed framework is designed as a structured decision support concept that transforms technical observations into lifecycle relevant management actions. Its logic contains five stages: acquisition of diagnostic data, extraction and normalization of condition indicators, interpretation of degradation related evidence, risk oriented categorization of safety status, and selection of lifecycle management actions with feedback for reassessment (Fig. 1). The design also reflects lessons from risk informed maintenance and structural health monitoring, where decision quality depends not only on measured condition but also on uncertainty, evidential confidence, and organizational risk tolerance [14], [15].

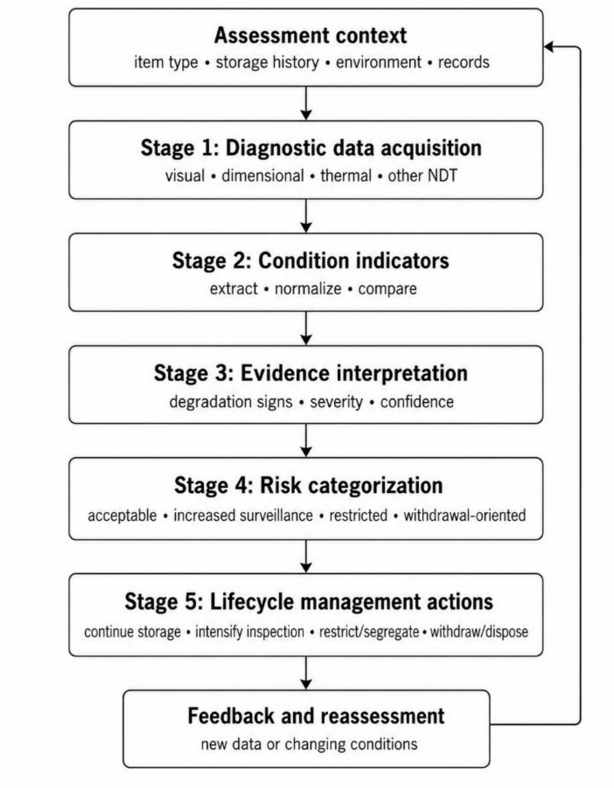

Fig. 1. Conceptual condition-based and risk-oriented lifecycle safety management framework with five-stage structure and feedback-driven reassessment loop.

A. General Structure of the Proposed Framework

The framework is organized as a multi stage assessment logic that links technical evidence to management action. It begins with the acquisition of non-destructive diagnostic data, continues through the formation and interpretation of condition indicators, and culminates in a risk oriented categorization that supports lifecycle decisions. A feedback loop is included to ensure that the safety status can be updated when new information becomes available.

B. Stage 1- Acquisition of Non Destructive Diagnostic Data

The first stage is focused on collecting technical evidence through non-destructive diagnostic methods applicable to the assessed ammunition items and their storage context. The objective is to obtain relevant condition information without invasive intervention or compromise of operational safety.

In ammunition applications, diagnostic acquisition should be planned as part of a larger surveillance concept rather than as an isolated reaction to a defect report. International guidance on stockpile surveillance and control of explosive facilities underlines that inspection planning must account for item type, storage history, environmental exposure, and local operating constraints [3], [4]. From a methodological perspective, this means that the value of a measurement depends not only on the sensing method itself but also on the inspection context and the consistency with which results are recorded and compared across time.

The literature on non-destructive testing further suggests that combining methods is often more informative than relying on a single source of evidence, especially when different techniques are sensitive to different classes of defects or degradation signatures [10]–[12]. In practical ammunition management, the appropriate combination may include visual examination, dimensional verification, thermal screening, vibration related observation, or other non-invasive approaches that are acceptable within the applicable safety regime.

C. Stage 2- Extraction and Normalization of Condition Indicators

Following data acquisition, the observed findings are transformed into condition indicators that capture technically meaningful aspects of the assessed state. To support comparability and structured interpretation, these indicators are normalized in a form suitable for subsequent evaluation.

Condition indicators should therefore be understood as an intermediate representation between raw inspection findings and management decisions. They make it possible to express technical evidence in a form that is comparable across inspections and easier to connect to lifecycle actions. This indicator perspective is consistent with broader engineering practice in condition monitoring, where the usefulness of data depends on its conversion into interpretable state descriptors rather than on raw signals alone [10], [11], [13], [15].

D. Stage 3- Interpretation of Degradation Related Evidence

At this stage, condition indicators are interpreted with respect to degradation patterns, possible ageing effects, and safety relevant anomalies. The goal is to establish whether the available evidence points to acceptable condition, increasing uncertainty, or signs of elevated technical concern.

Interpretation of degradation related evidence also requires sensitivity to the physical mechanisms that may evolve over long storage periods. Studies on ageing energetic binders and rocket propellant materials show that material behavior can change as a function of time, thermal history, and environmental exposure, and that such changes may be observed through non-destructive or minimally invasive characterization methods [13], [17], [18]. Although the present paper does not focus on one material family, these studies illustrate why lifecycle assessment must remain attentive to both observable anomalies and the uncertainty surrounding their evolution.

E. Stage 4- Risk Oriented Categorization of Safety Status

The interpreted evidence is then mapped to predefined safety categories using a risk oriented logic. This categorization provides an intermediate decision layer that connects technical findings with management relevance in a structured and auditable form.

The risk oriented categorization stage is conceptually aligned with the broader ammunition safety vocabulary used in international guidance, where risk reduction is explicitly linked to reducing both the probability and the consequences of undesirable explosive events [2], [4]. By introducing categories between raw findings and final action, the framework supports more transparent and repeatable judgments, especially in cases where the evidence is incomplete or where different stakeholders must justify the selected response.

F. Stage 5- Decision Support for Lifecycle Management Actions

Once the safety category is assigned, the framework supports the selection of corresponding lifecycle actions. These may include continued storage, increased inspection frequency, restrictions in handling or use, maintenance related intervention, segregation, or withdrawal from service.

Linking categories to actions is essential because the purpose of assessment is not only to describe condition but to guide management. In a lifecycle setting, these actions may range from continued storage with routine monitoring to intensified surveillance, segregation, controlled handling, maintenance oriented intervention, or preparation for disposal [5], [6], [9]. The framework is therefore decision centric: it treats technical assessment as a support process for safer and more rational stockpile governance.

G. Feedback Reassessment and Continuous Update

Because lifecycle status may evolve over time, the framework includes a feedback mechanism for repeated evaluation. New diagnostic evidence, changing storage conditions, or updated expert interpretation may justify reassessment and revision of the assigned risk category and related management action.

The published evidence therefore supports the logic of the proposed framework in three complementary ways. First, threshold-based chemical surveillance remains indispensable for identifying life-limiting degradation. Second, non-destructive dimensional and structural measurements already provide sub-millimetric resolution that is sufficient for screening geometry-sensitive components without invasive intervention. Third, thermomechanical characterization offers an interpretable bridge between observed material state and operational decision thresholds. On this basis, a practical risk-informed workflow should prioritize repeated measurement of the same indicators over time, because the decision value comes not only from one inspection result but from the trend and convergence of multiple evidence streams.

H. Analysis of Published Diagnostic Results

A further implication comes from shelf-life modelling studies on energetic materials. Using dynamic DSC data and model-based kinetic analysis, Sanchirico et al. reported that, under a 10 percent conversion failure threshold, the predicted shelf life of picric acid was about 4 months at 140 degrees C and about 12 years at 80 degrees C, while the same model yielded 58,800 years at 20 degrees C [20]. Although these values are material-specific and should not be transferred directly to conventional ammunition items, they demonstrate a practically important point for lifecycle management: temperature history strongly amplifies or suppresses degradation kinetics, and a risk-oriented framework should therefore treat storage environment and exposure history as decision-relevant variables rather than as background information only [20].

Published thermomechanical studies also provide operationally useful boundary values for risk categorization. In a 2024 dynamic mechanical analysis of double-base rocket propellant used in multi-barrel rocket systems, Cegla et al. determined a glass transition temperature of minus 27.48 degrees C and a softening temperature of 66.24 degrees C under the reported test conditions [17]. The same study concluded that these limits define the safe operating temperature range of the tested propellant and that increasing frequency and heating rate shifted the apparent transition temperatures toward higher values [17]. For lifecycle safety management, these findings are directly relevant because they show that the interpretation layer of the proposed framework should not only classify observed anomalies but also relate them to physically meaningful operating windows and to the measurement conditions under which those windows were derived [17].

A second group of results demonstrates the practical maturity of non-destructive methods for ammunition-related components. Pałka et al. developed a terahertz time-domain spectroscopy setup for artillery combustible cartridge cases and reported radius measurement uncertainty of 0.04 mm and wall-thickness uncertainty of 0.03 mm, with agreement against reference measurements [19]. These data are important for the present framework because they show that non-destructive inspection can already deliver quantitative evidence precise enough to populate condition indicators rather than merely qualitative screening notes. In a condition-based lifecycle workflow, this level of precision is sufficient to support category assignment when repeated measurements indicate dimensional drift, local wall degradation, or manufacturing non-uniformity relative to baseline values [18].

The analytical value of the proposed framework can be illustrated by comparing it with published surveillance results. Recent work on nitrocellulose-based propellants reiterates that acceptable long-term stability is commonly judged against explicit stabilizer-retention criteria. In a 2025 assessment of modified propellants, Cieslak et al. summarized the prevailing acceptance rule set as a maximum stabilizer depletion of 80 percent together with a minimum residual stabilizer content of 0.2 percent after aging [19]. From the perspective of the present framework, these criteria are important because they provide a concrete bridge between measured condition indicators and management thresholds: once residual stabilizer approaches the lower bound, an item should not remain in the same surveillance class as stock with clearly higher chemical reserve [19].

III. RESULTS AND DISCUSSION

The practical value of the proposed framework depends on the ability to convert diagnostic observations into interpretable indicators and then into management relevant risk categories. In real stockpile environments, diagnostic findings rarely have unambiguous meaning when considered in isolation. Their significance emerges only after they are interpreted in relation to likely degradation mechanisms, documented storage and handling conditions, and the possible safety implications for further lifecycle use [3], [4], [6], [9]. This section therefore discusses the evidence interpretation layer of the framework and explains how the resulting judgment can support prioritization and implementation in practice.

A. From Diagnostic Observations to Condition Indicators

Non-destructive diagnostic procedures typically generate raw observations, measured values, qualitative findings, or inspection notes. In their original form, such outputs are useful for documentation, but they are not always directly suitable for lifecycle decision making. A condition based framework requires an intermediate transformation step in which raw findings are expressed as indicators representing visible anomalies, dimensional deviations, environmental effects, instability patterns, or other signs of condition change. Reviews of non-destructive evaluation emphasize that this transformation is a prerequisite for consistent comparison, aggregation, and long term trend interpretation [10]–[12].

B. Interpretive Role of Degradation Related Evidence

Once condition indicators have been established, they must be interpreted in relation to degradation relevant mechanisms and safety concerns. The same observed feature may have different significance depending on its extent, recurrence, likely progression, and evidential confidence. Risk informed maintenance studies show that decisions under uncertainty should not be based on signal presence alone, but on a structured consideration of severity, consequence, confidence, and organizational risk tolerance [13], [14]. In the proposed framework, that logic is adapted to ammunition stockpile assessment by combining three interpretive dimensions: technical severity, safety relevance, and confidence of interpretation.

C. Risk Oriented Categorization Logic

After condition indicators have been interpreted, the resulting evidence is mapped to risk categories that provide a decision relevant representation of lifecycle safety status. The mapping is not purely mechanical. Rather, it is a structured judgment process in which indicator severity, safety significance, and evidential confidence are weighed together. This approach reflects the broader concept of risk management in ammunition guidance, where risk evaluation is part of the complete decision process and where surveillance, storage discipline, and protective measures are all elements of risk reduction [2], [3].

D. Proposed Risk Categories

For practical implementation, the framework can be expressed through four generic categories: acceptable condition, increased surveillance required, restricted safety status, and withdrawal oriented status. The first category supports continued storage under routine controls; the second indicates the need for shortened reassessment intervals or additional review; the third supports restrictions, segregation, or targeted intervention; and the fourth indicates that continued retention under normal conditions is no longer justified and that disposal or equivalent action should be considered [5], [6], [9]. Such categories are intentionally generic so that national or institutional procedures can refine the associated thresholds without losing the underlying logic.

E. Practical Applicability Prioritization and Implementation Constraints

The practical relevance of the framework depends not only on its conceptual consistency, but also on its applicability in real stockpile management environments. A useful methodology must support prioritization, remain compatible with existing procedures, and be implementable without assuming ideal data completeness. International guidance and life cycle management literature both note that heterogeneous records, variable storage environments, and uneven technical capacities are normal conditions rather than exceptions in ammunition management [1], [6]–[9]. Consequently, the framework is designed to improve judgment quality under realistic constraints, not to replace expert review with rigid automation.

F. Practical Applicability and Prioritization

The framework is applicable wherever there is a need to distinguish between items that may remain under routine control, items that require closer surveillance, and items that justify restrictions or withdrawal oriented action. This supports inspection prioritization under limited resources. In large stockpiles, not all items can be examined with equal frequency or depth. A risk oriented categorization enables resources to be directed toward items or groups associated with increasing uncertainty or higher potential consequence. That logic is consistent with both ammunition surveillance guidance and the wider literature on condition monitoring based maintenance [3], [12], [13], [14].

G. Traceability and Documentation Value

By requiring that risk categories be linked explicitly to condition indicators and interpretive reasoning, the framework supports a documented chain from technical evidence to management action. Such traceability improves internal consistency across repeated assessments, reduces reliance on undocumented ad hoc decisions, and creates a basis for auditability. It also supports communication between inspectors, logisticians, and decision makers by translating technical findings into a structured language of safety status and management response [6], [8], [9]. In this sense, the framework is not only an assessment tool, but also a governance tool.

H. Implementation Constraints

Implementation is subject to several constraints. The first limitation concerns data quality and heterogeneity. Some items may have detailed storage histories while others are associated with incomplete records. Diagnostic observations may differ in precision or comparability depending on the sensing method and local inspection conditions. The second limitation is organizational: even a well-structured framework requires clear roles, stable recording procedures, and sufficient technical competence to preserve repeatability. The broader sensor and health monitoring literature likewise notes that diagnostic usefulness is strongly influenced by data quality, sensor reliability, and the quality of the human interpretation process [11], [13], [14], [15].

I. Prospects for Digital Integration

Because the logic of the framework is based on condition indicators, category assignments, and documented reasoning, it can be progressively integrated into digital stockpile management environments. Even a basic digital registry can improve consistency compared with fragmented paper based practice by linking item identity, surveillance history, condition indicators, and reassessment intervals. Over time, such structuring can support more advanced decision support, trend analysis, and comparison across facilities. This direction also aligns with current international efforts that treat through life ammunition management as a system requiring sustainable national capabilities, evidence based planning, and follow up across the full lifecycle [8], [9].

A further implication of the proposed approach is methodological transferability. The framework is sufficiently generic to be adapted to different classes of conventional ammunition and to different maturity levels of national ammunition management systems. In lower capacity environments, it can function as a disciplined paper based workflow that improves consistency and prioritization. In more mature environments, it can support digitalized surveillance and lifecycle planning. This scalability is important because international guidance explicitly recognizes different levels of implementation capacity and promotes progressive improvement rather than one uniform solution [2], [8].

IV. CONCLUSIONS

This paper presented a condition-based and risk-oriented framework for lifecycle safety management of conventional ammunition using non-destructive diagnostic data as the primary source of technical evidence. The framework was developed to address practical challenges associated with ageing stockpiles, heterogeneous storage environments, incomplete historical information, and limited inspection resources.

The key findings can be summarized in three points. First, non-destructive diagnostic observations require an intermediate indicator layer in order to become comparable, traceable, and usable for lifecycle decisions. Second, risk-oriented categorization should combine technical severity, safety relevance, and confidence of interpretation rather than rely on isolated inspection results. Third, lifecycle management actions become more transparent when they are explicitly linked to documented categories such as acceptable condition, increased surveillance, restricted safety status, or withdrawal-oriented status.

The scientific contribution of the study is the formulation of a transferable assessment logic that connects diagnostic data, condition indicators, degradation interpretation, risk categories, and management actions within one auditable process. The practical implication is that stockpile managers can use the framework to prioritize inspections, justify restrictions or withdrawal, preserve decision traceability, and prepare the basis for digital decision support. Future work should extend the proposed concept through formalized indicator weighting, case-based validation, comparative evaluation of diagnostic techniques, and integration into digital stockpile management systems aligned with through-life ammunition management initiatives [8], [10]–[14].

ACKNOWLEDGMENT

This scientific report is funded by the Ministry of Education and Science in implementation of the Scientific Program „Security and Defence", adopted by Decree No. 731 of 21.10.2021 and pursuant to Agreement No. D01-74/19.05.2022.

The authors acknowledge the support and resources provided by Defence Institute for facilitating this study and appreciate the insightful discussions and feedback.

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