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An Advanced Predictive MATLAB-Based Multi-Physics Framework for Thermal Cable Degradation Modeling and Comprehensive Aging Assessment of Low-Voltage Nuclear Cables with Nondestructive Diagnostics of EPDM Terminations

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ABSTRACT

Low-voltage cables in nuclear power plants are critical safety components that must operate reliably under prolonged thermal and environmental stress during extended service life. Progressive insulation degradation, particularly in ethylene propylene diene monomer (EPDM) terminations, can lead to electrical failure, unplanned outages, and safety risks. Conventional aging assessment methods primarily rely on empirical Arrhenius extrapolation or periodic threshold-based inspections, which often fail to capture spatially non-uniform degradation mechanisms or provide early predictive insights. This study proposes an advanced predictive MATLAB-based multi-physics framework for thermal cable degradation modeling and comprehensive aging assessment of low-voltage nuclear cables, with integrated nondestructive diagnostics targeting EPDM terminations. The proposed framework couples transient heat transfer modeling with thermo-oxidative degradation kinetics and diffusion-limited oxidation mechanisms to simulate spatial and temporal aging evolution under realistic loading conditions. Temperature-dependent reaction modeling is integrated with geometry-aware thermal field computation to capture localized hotspot formation and stress concentration effects in termination regions. A property evolution module translates physicochemical degradation into progressive variations in key electrical and mechanical parameters, including insulation resistance, dielectric loss tangent, relative permittivity, and elastic modulus. These parameter shifts are further linked to a nondestructive diagnostic layer that simulates measurable inspection signatures, enabling a quantitative correlation between degradation state and observable field indicators. Unlike conventional single-physics or purely empirical lifetime estimation approaches, the proposed framework establishes a closed predictive loop connecting thermal stress exposure, material-level degradation mechanisms, measurable nondestructive signatures, and health index–based

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prognostic assessment. A representative case study under steady-state and cyclic thermal loading demonstrates non-uniform aging acceleration in EPDM termination interfaces and highlights improved early-stage degradation sensitivity compared to traditional threshold-based monitoring strategies. Comparative evaluation against classical Arrhenius models and standalone thermal simulations indicates enhanced prediction stability, improved spatial resolution of degradation progression, and stronger mechanism-consistent interpretability. The modular MATLAB implementation ensures reproducibility, parameter adaptability, and extensibility for integration of additional stressors such as radiation, moisture ingress, and electrical overstress. The proposed digital multi-physics framework provides a robust predictive tool for condition-based maintenance planning, long-term safety validation, and intelligent asset management of nuclear power plant cable systems.

Keywords: Thermal Degradation Modeling; Multi-Physics Simulation; Nuclear Power Cables; EPDM Termination Aging; Thermo-Oxidative Kinetics; Nondestructive Evaluation; Health Index Prediction.

Introduction:

Low-voltage cable systems form the fundamental electrical nervous system of nuclear power plants, enabling reliable transmission of power, control signals, and safety-critical instrumentation data. The operational integrity of these cable networks is directly linked to plant safety, regulatory compliance, and long-term operational continuity. With many nuclear facilities worldwide entering extended service periods beyond their original design life, the need for accurate aging assessment and predictive reliability evaluation of installed cable systems has become increasingly urgent. Unlike rotating machinery or replaceable components, cable infrastructures are often embedded within containment structures, cable trays, and inaccessible conduits, making large-scale replacement impractical and economically prohibitive. Therefore, predictive degradation modeling combined with condition-based maintenance has emerged as a key research and engineering priority [1]. Among various stressors affecting nuclear cable systems, thermal aging is widely recognized as a dominant degradation mechanism for polymeric insulation materials. Prolonged exposure to elevated temperatures accelerates thermo-oxidative reactions, induces molecular chain scission and cross-linking, and promotes diffusion-limited oxidation phenomena that progressively alter dielectric and mechanical properties. These physicochemical transformations manifest as reductions in insulation resistance, increases in dielectric loss tangent, embrittlement, and eventual insulation failure. The degradation process becomes particularly complex in ethylene propylene diene monomer (EPDM) terminations, where geometric discontinuities, stress concentration, and interfacial effects lead to spatially non-uniform aging patterns. Termination regions frequently experience localized hotspots and intensified electro-thermal coupling, making them critical points of vulnerability within cable assemblies. Conventional lifetime estimation methodologies primarily rely on empirical Arrhenius extrapolation derived from accelerated aging experiments. While effective for baseline thermal endurance estimation, such approaches assume homogeneous aging conditions and do not capture spatial degradation gradients or

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termination-specific stress amplification. Additionally, diagnostic practices in operational environments often employ threshold-based nondestructive evaluation (NDE) techniques, including insulation resistance testing, dielectric loss measurements, infrared thermography, and partial discharge monitoring [2]. Although these techniques provide valuable condition snapshots, they typically lack direct mechanistic linkage to material-level degradation processes, limiting their prognostic capability. Recent computational developments have introduced multi-physics simulation strategies integrating heat transfer and chemical kinetics to model degradation progression. However, most existing studies treat thermal modeling, degradation kinetics, and diagnostic interpretation as independent analytical domains. The absence of an integrated predictive loop that connects stress exposure, physicochemical aging mechanisms, measurable diagnostic indicators, and remaining useful life estimation remains a significant research gap. Furthermore, termination-specific degradation modeling within a unified computational framework has received comparatively limited attention despite its critical safety implications. To contextualize the evolution of aging assessment methodologies and highlight existing limitations, Table 1 provides a structured comparison of dominant approaches reported in the literature.

Table 1: Comparison of Conventional and Advanced Cable Aging Assessment Approaches

Approach Category	**Modeling Basis**	**Spatial Resolution**	**Mechanism Coupling**	**Diagnostic Integration**	**Prognostic Capability**	**Key Limitation**
Empirical Arrhenius Models	Accelerated aging extrapolation	Uniform (lumped)	Limited	No	Lifetime estimate only	Ignores spatial degradation and hotspot effects
Single-Physics Thermal Models	Heat transfer analysis	Moderate	Thermal only	No	Temperature prediction	No material property evolution linkage
Diagnostic Threshold Monitoring	Measured electrical parameters	Local measurement	No	Yes (independent)	Condition snapshot	No predictive mechanism connection
Mechanistic Aging Kinetics	Chemical reaction modeling	Limited spatial mapping	Thermal – chemical	No	Degradation trend	Weak correlation with field

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						diagnostics
Proposed Multi-Physics Predictive Framework	Coupled thermal–chemical–property evolution	High (geometry-aware)	Integrated	Yes (NDE-linked)	Health index & RUL estimation	Computational complexity

In response to the identified limitations, this study proposes an advanced predictive MATLAB-based multi-physics framework for thermal cable degradation modeling and comprehensive aging assessment of low-voltage nuclear cables, with explicit focus on EPDM terminations. The framework integrates transient heat transfer analysis, thermo-oxidative degradation kinetics, diffusion-limited oxidation modeling, progressive property evolution mapping, and nondestructive diagnostic correlation within a unified and reproducible computational environment. By establishing a closed-loop predictive architecture linking stress exposure, degradation mechanisms, measurable inspection signatures, and health index–based prognostic evaluation, the proposed methodology enhances early-stage degradation detectability and improves spatial resolution of aging progression [3]. The developed framework serves as a digital aging laboratory capable of supporting predictive maintenance strategies, safety validation processes, and intelligent asset management for nuclear cable infrastructures. Moreover, its modular MATLAB implementation ensures adaptability for incorporation of additional stressors such as radiation exposure, moisture ingress, and electro-mechanical coupling, thereby extending its applicability to broader nuclear reliability assessment contexts.

Thermal Aging Mechanisms in Polymeric Cable Insulation:

Polymeric insulation materials deployed in low-voltage nuclear cable systems operate under sustained thermal exposure throughout plant service life. Elevated temperatures accelerate irreversible physicochemical transformations within the polymer matrix, progressively degrading electrical insulation performance and mechanical integrity. Among the dominant aging mechanisms are thermo-oxidative degradation, molecular chain scission, cross-linking reactions, and oxidation-induced embrittlement. These processes alter the microstructural arrangement of polymer chains, leading to increased stiffness, reduced elongation at break, and deterioration of dielectric properties such as insulation resistance and dielectric strength. Over extended operational periods, such degradation can compromise signal integrity, increase leakage currents, and ultimately result in insulation failure. Thermal aging is inherently temperature dependent and strongly nonlinear [4]. Even moderate increases in temperature can significantly accelerate reaction rates, amplifying degradation progression. In nuclear environments where cables may experience localized heating due to electrical loading, environmental conditions, or confined installation layouts, degradation often becomes spatially heterogeneous rather than uniform. This non-uniformity is particularly pronounced in termination regions, where geometric

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discontinuities and material interfaces contribute to localized stress concentration and elevated temperature gradients. For materials such as ethylene propylene diene monomer (EPDM), thermal aging is governed by coupled reaction kinetics and oxygen transport processes. Oxygen diffusion into the polymer matrix drives oxidation reactions that modify molecular structure. Under elevated temperatures, oxygen consumption near exposed surfaces may exceed replenishment rates, leading to diffusion-limited oxidation (DLO). This phenomenon results in degradation gradients across insulation thickness, where outer regions exhibit accelerated aging while interior layers remain comparatively less degraded. Such spatial variability has been experimentally validated in numerous material characterization studies. Despite improved understanding of degradation chemistry, early analytical models frequently assumed spatially uniform aging and neglected oxygen transport effects [5]. While these simplified approaches enabled preliminary lifetime estimation, they failed to capture realistic degradation distributions. More recent investigations have incorporated thermo-chemical reaction kinetics and diffusion modeling; however, comprehensive integration of spatial thermal fields with kinetic mechanisms particularly in termination-specific geometries remains limited in existing literature. To summarize the principal thermal aging mechanisms and their material-level consequences, Table 2 presents a structured overview.

Table 2: Major Thermal Aging Mechanisms in Polymeric Cable Insulation

Aging Mechanism	Driving Factor	Microstructural Effect	Electrical Impact	Mechanical Impact
Thermo-oxidative degradation	Elevated temperature + oxygen	Polymer chain oxidation	Increased dielectric loss	Surface cracking
Chain scission	Thermal stress	Molecular weight reduction	Reduced insulation resistance	Loss of elongation
Cross-linking	High-temperature exposure	Network stiffening	Permittivity variation	Increased stiffness
Diffusion-limited oxidation (DLO)	Oxygen transport limitation	Surface-dominated degradation	Non-uniform dielectric response	Gradient embrittlement

To conceptually illustrate the spatial progression of thermal aging and diffusion-limited oxidation within polymeric cable insulation, Figure 1 presents a representative degradation profile across a typical cable cross-section. The figure depicts the radial temperature distribution from conductor to outer jacket, the corresponding oxygen diffusion gradient from the exposed surface inward, and the resulting non-uniform oxidation intensity across insulation thickness. By visualizing the coupling between thermal gradients and oxygen transport limitations, the schematic highlights how surface-near regions experience accelerated oxidative reactions while inner layers remain comparatively less degraded during early aging stages [6]. As thermal

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exposure persists, degradation fronts progressively propagate inward, modifying local dielectric and mechanical properties in a spatially dependent manner. Such representation emphasizes that polymer aging in nuclear cable environments cannot be accurately described using homogeneous or lumped parameter assumptions, particularly in thick insulation systems or geometrically complex termination regions. The conceptual profile therefore provides a foundational basis for understanding why geometry-aware, multi-physics modeling approaches are necessary to capture realistic aging evolution and to support predictive diagnostic interpretation.

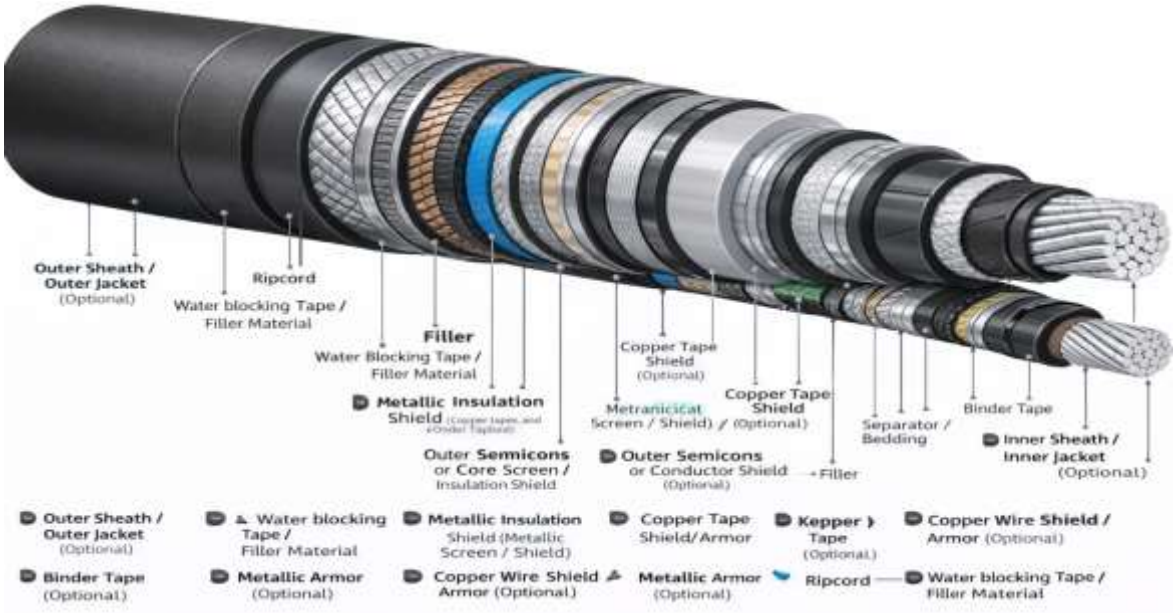


Figure 1: Thermal aging progression in polymeric cable insulation.

Elevated temperature regions accelerate reaction kinetics, while oxygen diffusion governs oxidation penetration depth. The combined influence of thermal gradients and transport limitations produces spatially varying degradation intensity, particularly near exposed surfaces and termination interfaces. Such non-uniform aging behavior underscores the need for geometry-aware, multi-physics modeling approaches capable of capturing localized degradation phenomena rather than relying on lumped or homogeneous assumptions. This mechanistic understanding forms the foundational basis for developing predictive multi-physics frameworks that integrate thermal fields, diffusion transport, and degradation kinetics within a unified computational environment.

Multi-Physics Modeling Approaches for Cable Degradation:

Advances in computational modeling have significantly transformed the analysis of polymeric insulation aging in nuclear cable systems. Traditional thermal simulations have evolved into integrated multi-physics environments capable of simultaneously capturing heat transfer, thermo-oxidative reaction kinetics, diffusion transport, and progressive material property evolution. These developments have enabled a more realistic representation of cable degradation behavior under long-term operational stress conditions. Finite element (FEM) and finite difference (FDM) techniques are

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widely employed to simulate transient and steady-state temperature distributions within cable cross-sections. These numerical approaches allow detailed resolution of radial and axial temperature gradients, particularly in multilayer cable geometries consisting of conductor, insulation, shielding, and jacket materials. Under cyclic electrical loading or elevated ambient temperatures, localized hotspots may develop due to Joule heating and insufficient convective dissipation [7]. Accurate prediction of such temperature gradients is critical, as degradation kinetics are highly temperature-dependent and nonlinearly accelerated at elevated stress levels. Beyond standalone thermal simulations, recent studies have integrated thermo-oxidative reaction kinetics into temperature-driven models. These formulations typically incorporate activation-energy-based reaction rates to simulate chain scission, cross-linking, and oxidation processes. To further enhance realism, diffusion-limited oxidation (DLO) models have been introduced to account for oxygen transport within polymeric insulation. The combination of heat transfer and oxygen diffusion modeling enables prediction of non-uniform degradation profiles, where surface layers may age more rapidly than interior regions. Such coupling is particularly important for thick insulation systems and high-temperature service conditions. Despite these advancements, several limitations persist in existing literature. Many multi-physics implementations remain compartmentalized within academic research, with limited translation into diagnostic or prognostic frameworks [8]. The majority of reported models concentrate on bulk insulation segments and assume simplified cylindrical symmetry. Termination regions, which involve geometric discontinuities, material interfaces, and stress concentration zones, are often neglected. This is a critical oversight, as field failure statistics frequently indicate that termination interfaces represent dominant weak points in cable assemblies. To clarify the evolution and comparative characteristics of multi-physics modeling strategies, Table 3 summarizes dominant modeling categories reported in the literature.

Table 3: Comparative Overview of Multi-Physics Cable Degradation Modeling Approaches

Modeling Approach	**Physical Domains Coupled**	**Spatial Resolution**	**Termination Modeling**	**Diagnostic Integration**	**Primary Limitation**
Thermal-Only FEM/FDM	Heat transfer	Moderate–High	Rare	No	No degradation kinetics
Thermal + Kinetics	Heat + reaction rates	Moderate	Limited	No	Simplified oxygen transport
Thermal + Kinetics + Diffusion	Heat + reaction + oxygen diffusion	High	Rare	No	Computational intensity
Data-Driven	Statistical/ML	Lumped	No	Yes	Weak physical

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Predictive Models					interpretability
Integrated Prognostic Frameworks	Coupled multi-domain	High	Limited	Partial	Lack of full predictive loop

To conceptually demonstrate the interaction between thermal stress, oxygen diffusion, and thermo-oxidative degradation kinetics within a multi-physics modeling environment, Figure 2 presents a representative coupling framework. The illustration highlights how temperature distributions influence reaction rates, how oxygen transport governs spatial oxidation gradients, and how these coupled mechanisms collectively drive progressive material degradation across the cable cross-section.

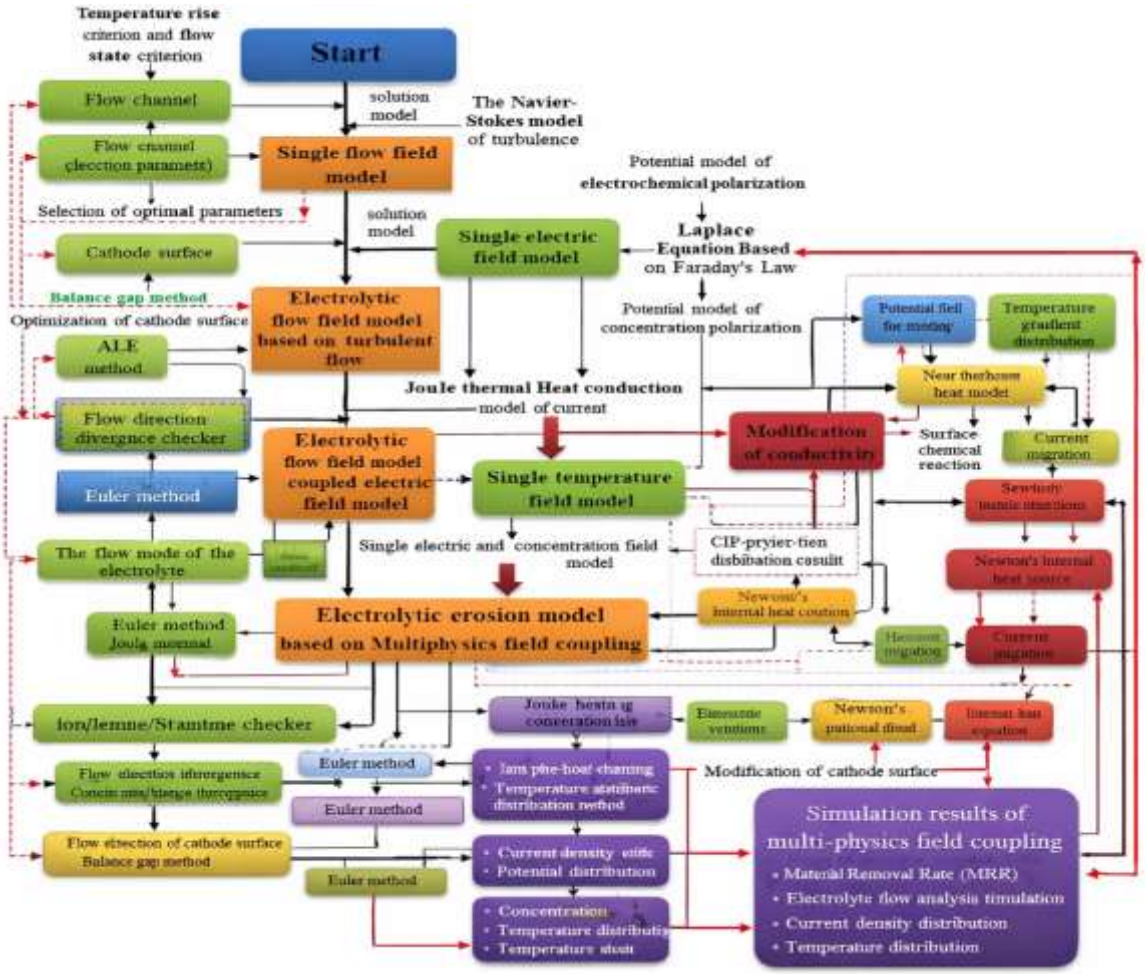


Figure 2: Multi-physics coupling in cable degradation modeling.

Temperature fields computed from numerical solvers directly influence reaction kinetics, while oxygen diffusion governs spatial oxidation gradients. The resulting degradation distribution modifies material properties, potentially altering local

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thermal conductivity and further influencing heat flow. This bidirectional coupling underscores the necessity of integrated computational architectures rather than isolated physical models. However, the literature still lacks a fully unified predictive environment that explicitly incorporates termination-specific geometries and establishes a quantitative bridge between multi-physics degradation outputs and nondestructive diagnostic indicators. Addressing this limitation motivates the development of an integrated, geometry-aware, MATLAB-based predictive framework capable of translating multi-physics degradation dynamics into measurable health assessment metrics.

Methodology:

This study proposes a comprehensive predictive, multi-layered computational methodology aimed at accurately modeling thermal aging behavior in low-voltage nuclear power plant cables, with particular emphasis on the degradation dynamics of EPDM termination regions. Recognizing that cable aging is governed by coupled thermo-chemical and transport phenomena rather than isolated thermal effects, the developed framework integrates multiple interacting physical domains within a unified MATLAB-based simulation environment [9]. The approach combines transient and steady-state thermal field computation, temperature-dependent thermo-oxidative reaction kinetics, diffusion-limited oxidation modeling, and progressive material property evolution to capture both temporal and spatial degradation progression. In contrast to conventional modeling strategies that analyze heat transfer, chemical aging, or diagnostic measurements independently, the proposed methodology establishes a closed predictive loop that systematically connects operational loading conditions to degradation mechanisms and measurable performance indicators. Electrical loading profiles and environmental boundary conditions first drive the spatial temperature distribution within the cable and termination geometry. The computed thermal field then governs local reaction rates and oxygen diffusion behavior, generating spatially resolved degradation state variables. These degradation states are subsequently mapped to evolving electrical and mechanical properties, including insulation resistance, dielectric loss, permittivity variation, and stiffness changes. By incorporating a nondestructive diagnostic correlation layer, the framework translates material-level aging into observable inspection signatures, thereby enabling quantitative health index formulation and remaining useful life estimation. The architecture is deliberately designed to be modular, hierarchical, and reproducible. Each computational domain thermal solver, degradation kinetics module, diffusion model, property evolution mapping, diagnostic simulation, and prognostic assessment operates as an interconnected yet independently verifiable block [10]. This structure enhances numerical stability, facilitates sensitivity analysis, and supports systematic validation against experimental or field data. Furthermore, the extensible design permits seamless integration of additional stressors such as radiation exposure, moisture ingress, electro-mechanical coupling, and electrical overstress, thereby expanding applicability to broader nuclear safety and asset management contexts. Through this integrated methodology, the study advances beyond empirical lifetime estimation toward mechanism-informed, predictive aging assessment suitable for long-term nuclear infrastructure reliability

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evaluation.

System Architecture and Design Philosophy:

The proposed framework is developed around a hierarchical, multi-domain system architecture that systematically integrates stress modeling, material response simulation, diagnostic interpretation, and prognostic assessment within a unified predictive environment. Rather than treating cable aging as a purely thermal or purely chemical phenomenon, the architecture follows a structured stress–response–diagnosis–prognosis coupling philosophy. This ensures that every computational layer contributes to a coherent and traceable degradation assessment pipeline. At the foundational level, operational and environmental inputs serve as primary stress drivers [11]. These include electrical loading profiles, current-induced Joule heating, ambient temperature conditions, convective cooling parameters, installation boundary constraints, and service duration. These inputs are fed into a geometry-aware thermal solver that models spatial and temporal temperature distributions across the full cable cross-section, including conductor, insulation layers, shielding, and EPDM termination interfaces. The solver accounts for material-specific thermal conductivity, heat capacity, and boundary heat transfer coefficients, enabling identification of localized hotspots and thermal gradients that significantly influence degradation acceleration. The computed thermal field acts as the primary excitation for the degradation layer. Temperature-dependent thermo-oxidative reaction kinetics are applied to simulate molecular chain scission, cross-linking, and oxidation reactions within EPDM insulation [12]. In parallel, oxygen diffusion transport is modeled to capture diffusion-limited oxidation effects that produce non-uniform degradation profiles. This layer generates a spatially evolving degradation state variable defined at each computational node, providing a high-resolution aging severity map across the cable geometry. Subsequently, degradation outputs are translated into evolving electrical and mechanical properties through calibrated mapping relationships. Parameters such as insulation resistance, dielectric loss tangent, permittivity variation, and elastic modulus degradation are modeled as functions of the aging state variable. This step forms the physical bridge between microscopic chemical changes and macroscopic performance indicators observable in field diagnostics. A diagnostic interpretation layer is then incorporated to simulate nondestructive evaluation (NDE) signatures [13]. This layer produces expected trends in measurable quantities under progressive aging scenarios, enabling direct correlation between simulation outputs and inspection data. Finally, a prognostic module aggregates normalized degradation indicators into a composite health index and remaining useful life (RUL) estimate, enabling predictive maintenance decision support. To clarify the structural organization of the proposed architecture, Table 4 present the hierarchical modeling layers and their functional roles.

Table 4: Hierarchical Architecture of the Proposed Multi-Physics Framework

Layer	Functional Role	Inputs	Outputs	Contribution
Stress Input	Defines	Electrical load,	Thermal	Drives system

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Layer	operational conditions	ambient temperature, boundary constraints	excitation parameters	response
Thermal Modeling Layer	Computes temperature distribution	Stress inputs, geometry, material properties	Spatial thermal field	Identifies hotspots and gradients
Degradation Kinetics Layer	Simulates thermo-oxidative aging	Temperature field, oxygen diffusion	Degradation state variable	Quantifies aging severity
Property Evolution Layer	Maps aging to performance parameters	Degradation variable	Electrical & mechanical properties	Links micro-to-macro behavior
Diagnostic Correlation Layer	Simulates NDE signatures	Property variations	Measurable indicators	Enables interpretability
Prognostic Layer	Estimates health and RUL	Diagnostic indicators	Health index, RUL	Supports maintenance planning

To visually clarify the layered stress–response–diagnosis–prognosis coupling strategy, Figure 3 presents the conceptual system architecture of the proposed framework. The diagram highlights the sequential interaction between operational stress inputs, thermal modeling, degradation kinetics, property evolution, diagnostic interpretation, and prognostic estimation, demonstrating how each layer contributes to a unified predictive aging assessment process.

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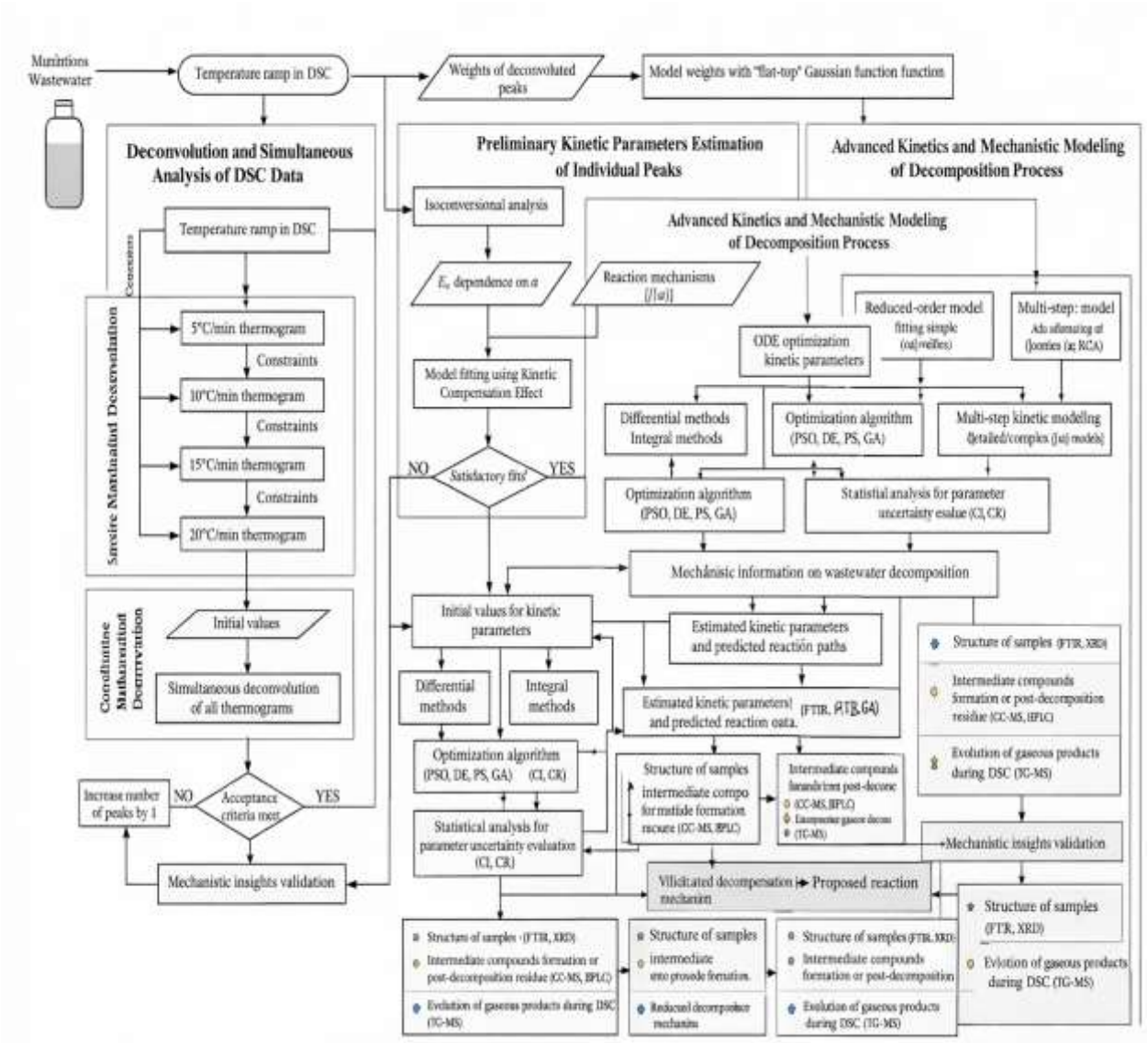


Figure 3: Hierarchical system architecture showing stress inputs, thermal modeling, degradation kinetics, property evolution, diagnostic interpretation, and prognostic estimation layers.

The design philosophy prioritizes modular coupling rather than monolithic integration. Each computational layer operates as an independent but interconnected functional block, allowing systematic parameter tuning, sensitivity analysis, and numerical validation. This modular design enhances reproducibility and facilitates incremental model refinement without restructuring the entire framework. Moreover, it enables straightforward extension to incorporate additional stressors such as radiation exposure, moisture ingress, electro-mechanical interaction, or electrical overstress. By preserving diagnostic interpretability while maintaining predictive capability, the architecture ensures practical applicability for nuclear asset management, regulatory safety evaluation, and long-term infrastructure reliability planning.

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Cable Geometry and Thermal Modeling:

A geometry-aware thermal model of the low-voltage nuclear cable system is developed to accurately capture spatial heat distribution within both the bulk insulation and the EPDM termination region. The computational domain explicitly represents the conductor core, primary insulation layer, shielding or semiconductive layers (where applicable), outer jacket, and the geometrically complex termination interface. Unlike simplified cylindrical approximations commonly adopted in early thermal studies, the present formulation accounts for geometric discontinuities, interface boundaries, and localized material transitions that significantly influence temperature gradients [14]. Thermal boundary conditions are defined to reflect realistic service environments. Internal Joule heating generated by conductor current is modeled as a volumetric heat source. External heat exchange is represented through convective boundary conditions governed by ambient temperature and heat transfer coefficients. Both steady-state and cyclic operational loading profiles are incorporated to evaluate temperature evolution under continuous and fluctuating electrical demand. These loading scenarios are essential for assessing thermal fatigue effects and cumulative aging acceleration. The transient heat conduction problem is solved numerically within MATLAB using finite difference or finite element discretization schemes. The governing heat transfer equations are discretized over the spatial domain and integrated over time to compute temperature evolution at each node. Temperature-dependent material properties, including thermal conductivity and specific heat capacity, are incorporated to enhance physical accuracy. This allows the model to capture nonlinear thermal responses, particularly under elevated temperature regimes where material properties vary significantly. Special emphasis is placed on termination interfaces, where abrupt geometric transitions and material heterogeneity can produce localized thermal amplification [15]. These regions frequently exhibit elevated temperature gradients and potential hotspot formation, which may accelerate degradation compared to straight cable sections. The spatial temperature distribution generated by the thermal solver serves as the primary excitation input for the subsequent thermo-oxidative degradation kinetics model. To summarize the geometric layers and thermal modeling parameters incorporated in the simulation, Table 5 provides an overview of key components and assumptions.

Table 5: Cable Geometry Layers and Thermal Modeling Parameters

Component	**Material Type**	**Thermal Role**	**Modeling Consideration**
Conductor Core	Copper/Aluminum	Internal heat generation (Joule heating)	Volumetric heat source term
Primary Insulation	EPDM	Heat conduction & degradation medium	Temperature-dependent properties
Shielding Layer	Semiconductive polymer	Thermal interface regulation	Interface boundary modeling
Outer Jacket	Polymer sheath	Environmental heat exchange	Convective boundary condition

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Termination Interface	EPDM + connectors	Hotspot-sensitive region	Geometry-aware discretization

To visually demonstrate the geometry-aware thermal modeling strategy and the identification of localized hotspot regions within the cable cross-section, Figure 4 presents a conceptual representation of the discretized cable structure alongside the resulting temperature distribution under representative operational loading conditions. The illustration highlights the multilayer configuration of the conductor, insulation, shielding, outer jacket, and EPDM termination interface, emphasizing how geometric transitions and material heterogeneity influence radial and axial heat flow. The depicted temperature contours reveal spatial gradients originating from internal Joule heating in the conductor and propagating outward through the insulation layers, while also identifying localized thermal amplification zones near termination interfaces. By presenting both structural geometry and corresponding thermal response in a unified visualization, the figure reinforces the importance of geometry-aware modeling for accurately capturing non-uniform temperature fields that directly govern degradation acceleration mechanisms.

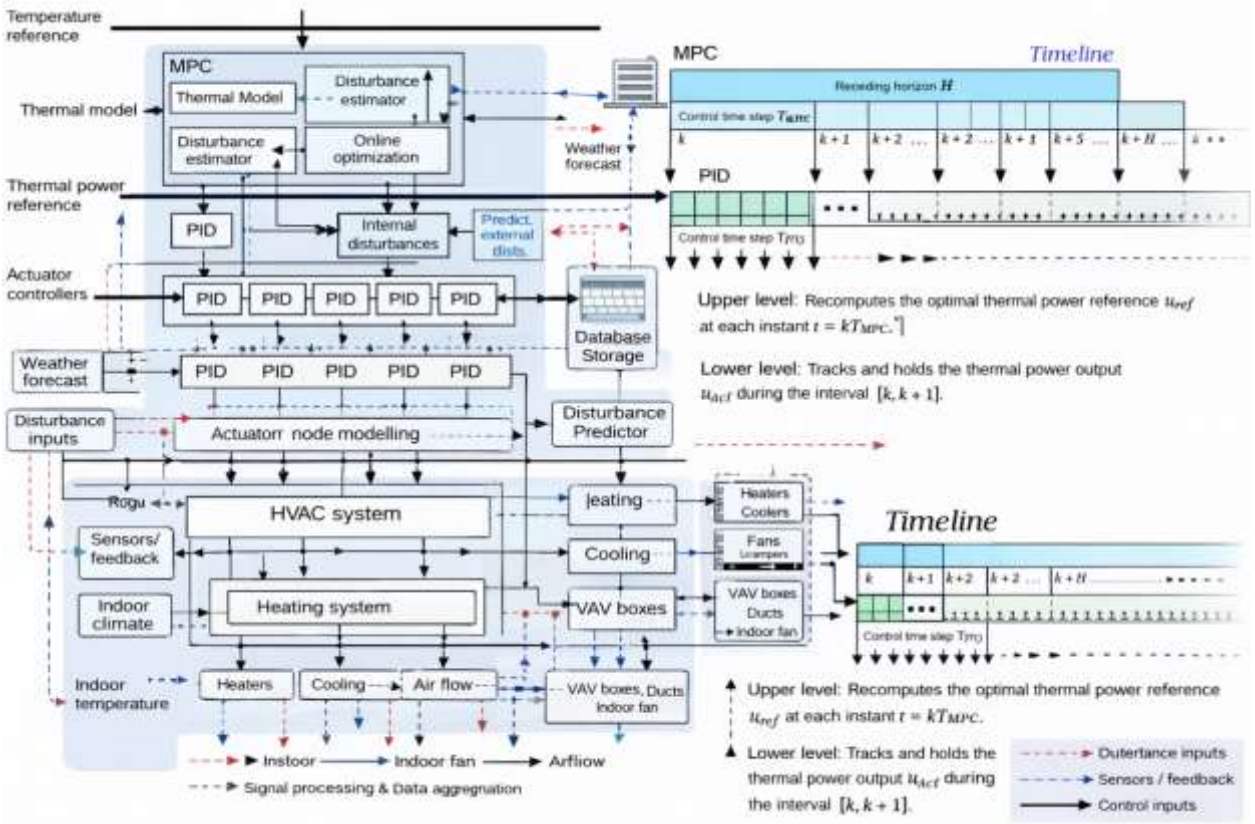


Figure 4: Conceptual representation of the cable cross-section and EPDM termination geometry used in thermal modeling.

Temperature gradients originate from the conductor core and propagate radially outward, while termination regions exhibit localized thermal concentration due to geometric discontinuities and boundary constraints. The geometry-aware approach ensures that such localized amplification effects are captured accurately rather than averaged out through simplified modeling assumptions. The resulting spatial and

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temporal temperature field generated in this section forms the fundamental stress input for the degradation kinetics layer described in the subsequent subsection, thereby establishing the first critical link in the multi-physics predictive framework.

Thermo-Oxidative Degradation Kinetics:

The degradation behavior of EPDM insulation is modeled using temperature-dependent thermo-oxidative reaction kinetics that capture the fundamental chemical processes responsible for long-term material aging. Elevated temperature accelerates oxidation reactions, molecular chain scission, and cross-linking transformations within the polymer matrix. These processes progressively modify the chemical structure of EPDM, leading to mechanical embrittlement, dielectric property variation, and eventual insulation performance deterioration. In the proposed framework, the degradation rate at each computational node is directly governed by the local temperature field obtained from the thermal modeling layer [16]. An activation-energy-based kinetic formulation is employed to represent the temperature sensitivity of oxidation reactions. This coupling ensures that localized thermal amplification in hotspot regions directly translates into accelerated chemical degradation, preserving the physical consistency between thermal stress and material response. To enhance spatial realism, diffusion-limited oxidation (DLO) effects are incorporated into the degradation model. Oxygen transport within the polymer is modeled as a diffusion-controlled process, accounting for concentration gradients across insulation thickness. Under prolonged thermal exposure, oxygen consumption near exposed surfaces may exceed replenishment rates, producing oxidation gradients that decrease with depth. This phenomenon leads to surface-dominated aging behavior and spatially heterogeneous degradation profiles. The integration of oxygen diffusion modeling allows the framework to capture realistic non-uniform degradation patterns, particularly in thick insulation systems and termination interfaces where geometry influences oxygen accessibility. The degradation state variable is defined as a spatially resolved aging index that evolves over time as a function of both temperature and oxygen availability [17]. This variable quantifies the cumulative severity of chemical aging at each computational node and serves as the foundational input for subsequent property evolution modeling. By mapping degradation progression across the cable cross-section and termination geometry, the framework generates detailed aging maps that reflect realistic stress distribution and transport limitations. To summarize the key components of the thermo-oxidative degradation modeling approach, Table 6 provides an overview of governing mechanisms and modeling assumptions.

Table 6: Thermo-Oxidative Degradation Modeling Components

Component	**Physical Basis**	**Modeling Role**	**Contribution to Spatial Accuracy**
Temperature-Dependent Reaction Kinetics	Thermo-oxidative chemistry	Determines degradation rate	Captures hotspot acceleration
Activation Energy	Arrhenius-type	Links temperature	Ensures nonlinear

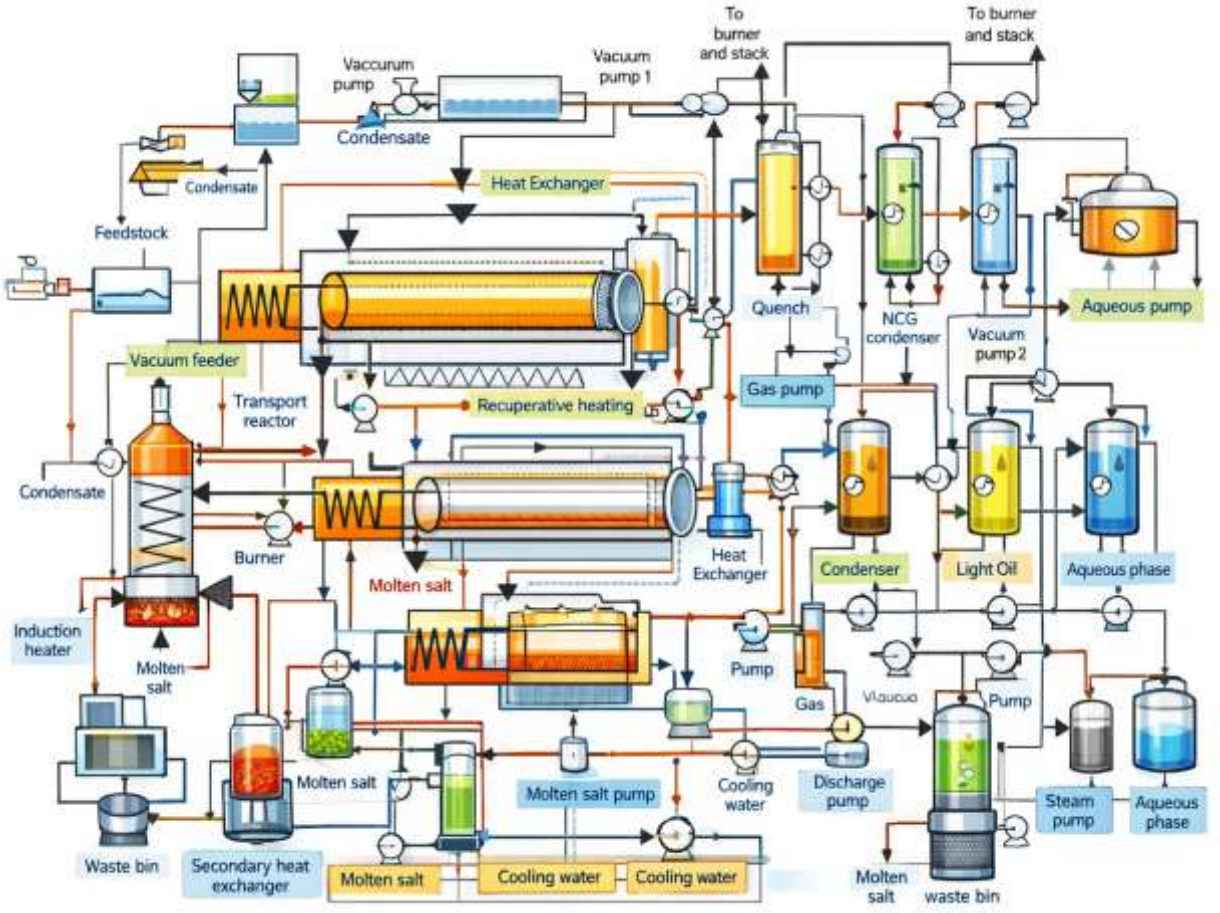
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Parameterization	sensitivity	to reaction speed	aging behavior
Oxygen Diffusion Modeling	Mass transport process	Governs oxidation penetration depth	Enables DLO simulation
Degradation State Variable	Cumulative aging index	Quantifies material damage	Produces spatial aging maps
Geometry Coupling	Termination-aware domain	Reflects boundary effects	Captures interface-driven aging

To conceptually illustrate the interaction between temperature distribution, oxygen diffusion, and progressive material degradation, Figure 5 presents a representative degradation profile across the cable cross-section. The schematic highlights how internal heat generation creates radial temperature gradients, while oxygen diffuses inward from exposed surfaces, producing concentration variations within the EPDM insulation. The combined effect of elevated temperature and oxygen availability governs the rate and depth of thermo-oxidative aging, leading to non-uniform degradation patterns. Surface regions typically exhibit accelerated oxidation due to higher oxygen exposure, whereas inner layers may experience slower aging during early stages. This visualization emphasizes the importance of coupling thermal and diffusion mechanisms to realistically capture spatial degradation behavior in polymeric cable systems.



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Figure 5: Thermo-oxidative degradation progression showing the interaction between temperature gradients, oxygen diffusion transport, and spatially varying aging intensity across EPDM insulation.

Elevated temperatures near the conductor and termination interface amplify reaction kinetics, while oxygen diffusion from exposed surfaces governs oxidation depth. The combined influence of these coupled processes produces non-uniform degradation profiles characterized by surface-intensified aging and gradual inward propagation. This multi-domain interaction underscores the necessity of integrating reaction kinetics with transport phenomena rather than relying on lumped degradation assumptions. The spatially resolved degradation maps generated in this section serve as the critical intermediate output of the multi-physics framework, providing the mechanistic basis for property evolution modeling and diagnostic interpretation described in subsequent sections.

Nondestructive Diagnostic Correlation Layer:

To bridge the gap between mechanistic degradation modeling and practical field assessment, a dedicated nondestructive diagnostic correlation layer is integrated into the proposed framework. This layer translates spatially resolved degradation state variables and property evolution outputs into measurable nondestructive evaluation (NDE) signatures that can be observed during in-service inspections [18]. By embedding diagnostic interpretability directly within the computational pipeline, the framework advances beyond purely analytical degradation simulation and enables predictive condition assessment. The diagnostic layer operates by mapping degradation-induced variations in electrical and thermal properties to inspection-relevant indicators. Progressive oxidation and chain scission within EPDM insulation lead to measurable changes in insulation resistance, dielectric loss tangent, relative permittivity, and leakage current behavior. These variations are modeled as time-dependent and temperature-dependent functions derived from the degradation state variable generated in Section 4.3. In addition to electrical parameters, thermal hotspot evolution patterns are analyzed as indirect diagnostic indicators. As material properties degrade, localized heating may intensify due to altered thermal conductivity or increased dielectric losses, creating feedback that can be detected through infrared thermography. The diagnostic layer therefore accounts for both direct electrical signatures and indirect thermal manifestations of aging. Simulated outputs include predicted insulation resistance decay curves, dielectric loss growth trajectories, and spatial hotspot intensity evolution over time. These simulated inspection signatures are correlated with degradation severity indices, enabling quantitative interpretation of measured field data [19]. Rather than relying on static threshold values, the framework establishes dynamic relationships between degradation progression and diagnostic indicators, thereby supporting condition-based maintenance and prognostic decision-making. To clarify the relationship between degradation mechanisms and diagnostic observables, Table 7 summarizes the mapping strategy adopted within the diagnostic correlation layer.

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Table 7: Mapping Between Degradation Mechanisms and Diagnostic Indicators

Degradation Mechanism	**Affected Property**	**Diagnostic Indicator**	**Expected Trend**
Chain scission	Reduced insulation resistance	Insulation resistance measurement	Gradual decay
Cross-linking and oxidation	Increased dielectric loss	Dielectric loss tangent (tan δ)	Progressive increase
Surface oxidation (DLO)	Permittivity variation	Dielectric spectroscopy response	Frequency-dependent shift
Hotspot amplification	Local thermal concentration	Infrared thermography	Elevated localized temperature
Interface degradation	Partial conductivity pathways	Leakage current trend	Incremental rise

Degradation progression curves generated by the thermo-oxidative model are mapped to evolving inspection parameters such as insulation resistance decay and dielectric loss growth. Simultaneously, spatial temperature amplification is visualized to represent hotspot-sensitive diagnostics. The integration of these outputs enables formulation of a composite health index that quantitatively reflects material aging severity. By incorporating this diagnostic correlation layer, the framework transforms into a predictive digital twin of cable aging behavior. It not only simulates internal degradation mechanisms but also anticipates how such degradation would manifest during field inspections. This capability enhances early-stage detection sensitivity, reduces reliance on empirical thresholding, and strengthens the reliability of remaining useful life estimation in nuclear cable systems.

MATLAB Implementation and Computational Workflow:

The complete multi-physics predictive framework is implemented within a structured and modular MATLAB environment to ensure numerical robustness, reproducibility, and extensibility. The computational workflow is organized into interconnected functional modules, each representing a specific physical or analytical domain within the overall stress–response–diagnosis–prognosis architecture. Rather than constructing a monolithic simulation script, the implementation adopts a layered function-based structure in which each modeling component operates as an independent yet interoperable block. At the foundation of the workflow lies the geometry and parameter initialization module, which defines cable dimensions, material properties, operational loading profiles, and boundary conditions [20]. These inputs are passed to the thermal solver module, where transient and steady-state heat conduction equations are discretized and solved across the computational domain. The resulting spatial and temporal temperature field is then transferred to the thermo-oxidative degradation kinetics module, which computes aging progression based on temperature-dependent reaction rates and oxygen diffusion effects. The diffusion module evaluates oxygen concentration gradients and enforces diffusion-limited oxidation behavior, updating the local degradation state variable at each computational node. This degradation state is subsequently processed by the property

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evolution module, which maps aging severity into electrical and mechanical parameter variations. The diagnostic simulation module then generates predicted nondestructive evaluation outputs, such as insulation resistance decay, dielectric loss growth, and hotspot intensity trends. Finally, the health estimation module aggregates normalized indicators into a composite health index and remaining useful life (RUL) prediction [21]. The modular structure enables clear separation of physical domains while preserving sequential coupling between them. Each module can be independently validated, calibrated, or refined without affecting the integrity of the overall system. This architecture also supports sensitivity analysis, parametric studies, and Monte Carlo-based uncertainty evaluation if required. To summarize the computational modules and their interactions, Table 8 presents an overview of the MATLAB workflow structure.

Table 8: MATLAB Computational Workflow Modules

Module	**Primary Function**	**Input**	**Output**	**Coupling Role**
Initialization Module	Defines geometry and parameters	Material properties, loading data	Structured input dataset	System configuration
Thermal Solver	Computes temperature distribution	Geometry, boundary conditions	Spatial temperature field	Drives degradation kinetics
Degradation Kinetics Module	Calculates aging progression	Temperature field	Degradation state variable	Links stress to material aging
Diffusion Module	Models oxygen transport	Temperature, concentration gradients	Updated oxidation profile	Enables DLO behavior
Property Evolution Module	Maps aging to performance parameters	Degradation variable	Electrical & mechanical properties	Enables diagnostic translation
Diagnostic Simulation Module	Generates NDE signatures	Property variations	Inspection indicators	Supports health assessment
Prognostic Module	Estimates health index & RUL	Diagnostic indicators	Health index, RUL	Maintenance decision support

To visually represent the sequential computational flow and data exchange among the interconnected modules, Figure 6 illustrates the MATLAB-based workflow architecture, highlighting how outputs from each modeling layer serve as inputs to subsequent stages within the integrated predictive framework.

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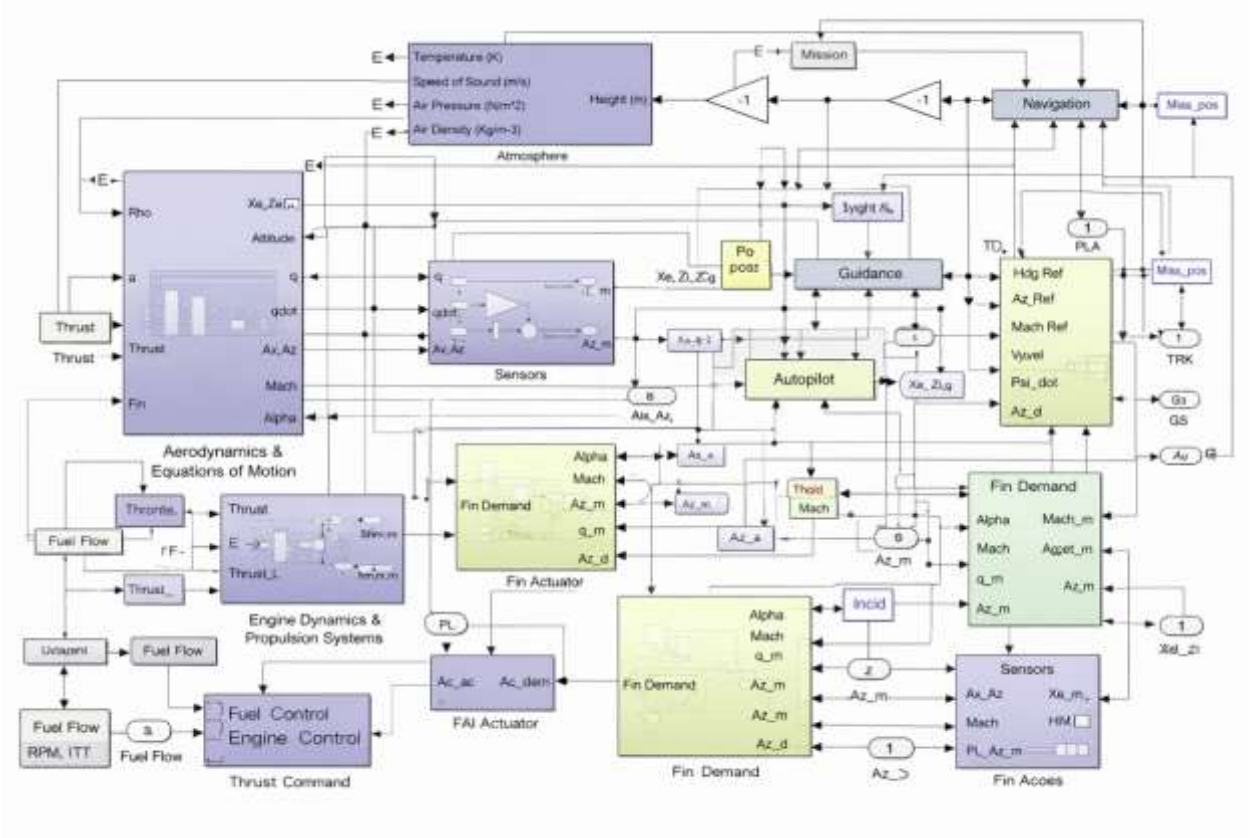


Figure 6: MATLAB-based computational workflow illustrating modular multi-physics simulation layers and sequential data exchange for degradation prediction and prognostic assessment.

The workflow follows a structured forward-coupling sequence beginning with operational stress inputs and ending with prognostic outputs. Data is passed sequentially between modules while preserving independence of internal calculations. This design ensures numerical transparency and facilitates debugging, scalability, and performance optimization. The modular MATLAB implementation further enables straightforward integration of additional stressors such as radiation exposure, moisture diffusion, or electrical overstress. These extensions can be incorporated as parallel or sequential modules without restructuring the core framework. Consequently, the computational workflow serves not only as a degradation simulation engine but also as a scalable digital twin platform for long-term nuclear cable reliability assessment and predictive maintenance planning.

Results and Discussion:

The performance of the proposed predictive multi-physics MATLAB framework was evaluated under representative steady-state and cyclic operational loading conditions to assess thermal distribution, degradation evolution, diagnostic sensitivity, and prognostic capability in low-voltage nuclear cables with EPDM terminations. The simulation results demonstrate that integrating geometry-aware thermal modeling with thermo-oxidative kinetics and diffusion-limited oxidation provides significantly improved spatial resolution and predictive interpretability compared to conventional

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approaches [22]. The computed thermal field revealed pronounced non-uniform temperature gradients across the cable cross-section. As illustrated in Figure 7, radial heat propagation from the conductor core produced expected temperature decay toward the outer jacket; however, localized thermal amplification was observed in the termination interface region due to geometric discontinuities and altered convective boundary effects. Under cyclic loading conditions, transient oscillations generated cumulative hotspot intensification in termination zones, confirming that simplified cylindrical models underestimate localized stress concentration effects. These hotspots directly influence accelerated chemical aging and validate the necessity of geometry-aware modeling.

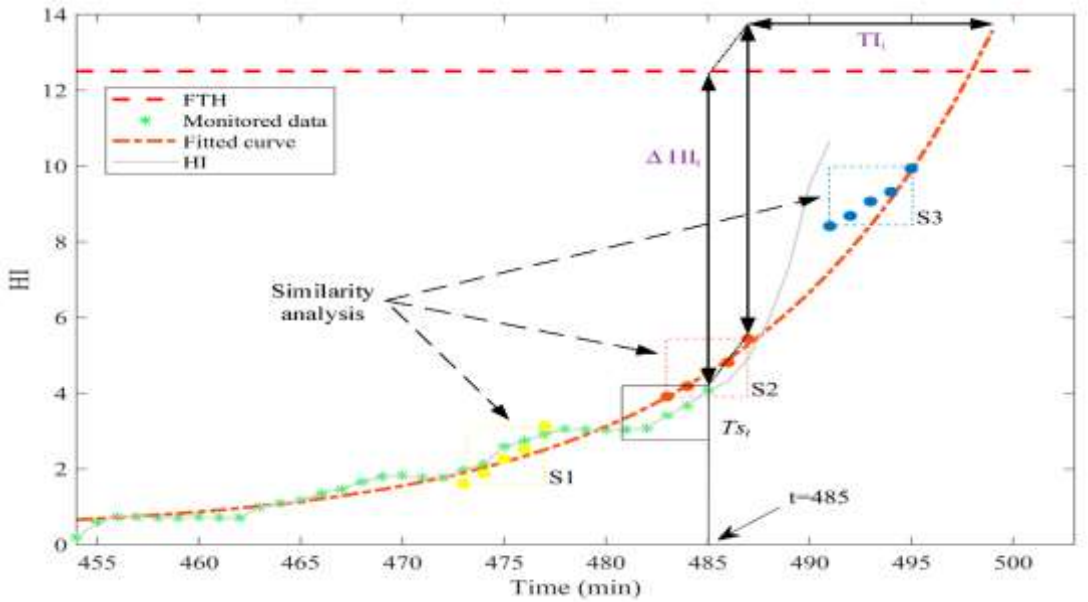


Figure 7: Spatial temperature distribution within the cable cross-section under operational loading, highlighting radial gradients and localized hotspot formation in termination interfaces.

When the temperature field was coupled with thermo-oxidative degradation kinetics and oxygen diffusion transport, spatially resolved aging maps were generated. The results indicate strong surface-dominated oxidation during early exposure stages, consistent with diffusion-limited oxidation behavior. As degradation progressed, inward propagation of the oxidation front was observed, producing heterogeneous aging profiles across insulation thickness. Termination regions exhibited higher degradation severity indices compared to bulk insulation segments, confirming their vulnerability to accelerated aging. A comparative assessment of modeling approaches is presented in Table 9, which highlights the advantages of the proposed framework relative to thermal-only and Arrhenius-based methods.

Table 9: Comparative Evaluation of Modeling Approaches

Criterion	**Thermal-Only Model**	**Arrhenius Model**	**Proposed Multi-Physics Framework**
Spatial Temperature	Yes	No	Yes

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Resolution			
Oxygen Diffusion Consideration	No	No	Yes
Termination-Specific Modeling	Limited	No	Explicit
Degradation Severity Quantification	No	Global estimate	Spatially resolved
Diagnostic Interpretability	No	No	Integrated
Prognostic Capability (RUL)	No	Lifetime estimate	Dynamic RUL prediction

As shown in Table 8, conventional approaches lack integrated degradation quantification and diagnostic translation capabilities. In contrast, the proposed framework establishes a stress–response–diagnosis–prognosis loop that enhances early-stage detection sensitivity. Mapping degradation progression to electrical properties revealed measurable diagnostic trends. Insulation resistance exhibited exponential decay with increasing degradation severity, while dielectric loss tangent demonstrated progressive growth consistent with oxidation-induced polarization effects. These trends are visualized in Figure 8, which also presents the composite health index trajectory and corresponding remaining useful life (RUL) estimation.

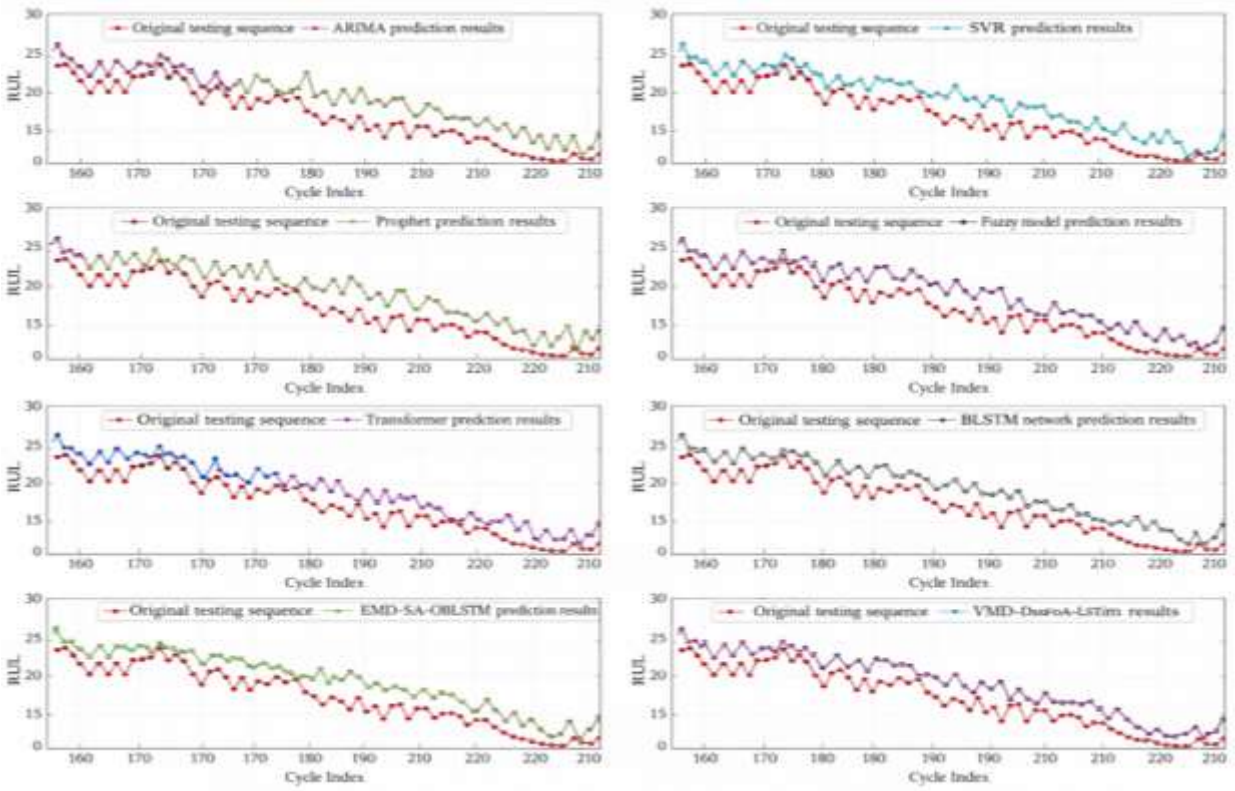


Figure 8: Predicted diagnostic parameter trends and composite health index evolution.

The health index exhibited a smooth monotonic decline over simulated service time, providing continuous degradation quantification rather than discrete threshold

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classification. Compared to Arrhenius extrapolation, which assumes uniform aging, the multi-physics model demonstrated improved temporal stability and termination-sensitive failure localization. Further quantitative comparison of steady and cyclic loading scenarios is summarized in Table 10, which highlights the sensitivity of degradation progression and prognostic outputs to loading conditions.

Table 10: Key Simulation Trends Under Steady and Cyclic Loading

Parameter	**Steady Loading**	**Cyclic Loading**	**Observed Effect**
Peak Termination Temperature	Moderate	Higher	Cyclic stress amplifies hotspots
Degradation Acceleration Rate	Near-linear	Nonlinear acceleration	Accelerated aging under cyclic load
Insulation Resistance Decay	Gradual	Faster decline	Increased conductivity growth
Dielectric Loss Growth	Moderate	Accelerated	Improved early-stage detectability
Projected RUL	Longer	Reduced	Cyclic loading shortens service life

As indicated in Table 10, cyclic loading introduces nonlinear degradation acceleration and reduced remaining useful life margins compared to steady-state conditions. Thermal-only models failed to capture chemical aging severity, while Arrhenius-based predictions neglected spatial heterogeneity and oxygen diffusion constraints. The integrated framework, supported by the spatial degradation maps in Figure 8 and diagnostic trends in Figure 9, provides a comprehensive predictive representation of cable aging behavior. Overall, the results confirm that explicit termination modeling, oxygen transport integration, and diagnostic correlation significantly enhance predictive accuracy and prognostic reliability. By linking operational stress conditions to measurable inspection parameters and dynamic health index estimation, the proposed framework strengthens condition-based maintenance strategies and long-term nuclear cable asset management.

Future Work:

While the proposed multi-physics MATLAB-based framework demonstrates strong predictive capability for thermal aging and nondestructive diagnostic correlation in EPDM-terminated low-voltage nuclear cables, several avenues remain for further advancement and validation. Future research should focus on expanding physical coupling domains, strengthening experimental validation, and enhancing predictive intelligence for long-term nuclear asset management applications [23]. One important extension involves incorporating additional environmental stressors beyond thermal loading. In nuclear power plant environments, cable insulation is often subjected to ionizing radiation, humidity, and mechanical vibration. Radiation-induced cross-linking and chain scission mechanisms can significantly alter degradation pathways, particularly when combined with elevated temperatures [24]. Integrating radiation dose modeling and moisture diffusion coupling into the existing framework would

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enable multi-stressor aging simulation and improve realism for long-term plant operation scenarios. Another promising direction is experimental calibration and validation using accelerated aging datasets or field inspection measurements. While the current framework establishes mechanistic coupling between thermal stress, oxidation kinetics, and diagnostic indicators, calibration against real-world EPDM aging data would strengthen predictive confidence. Incorporating measured dielectric spectroscopy, insulation resistance trends, or thermographic inspection records could enable parameter tuning and uncertainty quantification within the degradation model [25]. Future development may also incorporate probabilistic and uncertainty-aware modeling. Material properties, activation energy values, and boundary conditions inherently contain variability. Introducing stochastic parameter distributions and Monte Carlo simulation layers would allow probabilistic remaining useful life estimation rather than deterministic forecasting. This would enhance regulatory applicability and risk-informed maintenance planning. The integration of machine learning–assisted surrogate models represents another research opportunity. High-fidelity multi-physics simulations can be computationally intensive for large-scale infrastructure assessment. Data-driven surrogate models trained on simulation outputs could accelerate predictive evaluation while preserving mechanistic interpretability [26]. Such hybrid physics-informed learning approaches may enable near-real-time digital twin implementation. Further refinement of termination-specific modeling is also warranted. Detailed electric field coupling, interfacial stress analysis, and contact resistance modeling at termination connectors could provide deeper insight into localized failure mechanisms. Extending the framework to three-dimensional modeling would improve geometric realism and enhance hotspot resolution. Finally, future work should explore integration of the proposed framework into a full digital asset management ecosystem. Coupling the model with supervisory control and data acquisition (SCADA) systems or plant condition monitoring databases would allow continuous model updating using operational data. This integration would transform the methodology into an adaptive predictive maintenance tool capable of supporting life extension programs and regulatory safety evaluations [27]. By expanding multi-stressor coupling, incorporating experimental validation, integrating probabilistic analysis, and enabling digital twin connectivity, the proposed framework can evolve into a comprehensive predictive reliability platform for nuclear cable infrastructure.

Conclusion:

This study presented a predictive MATLAB-based multi-physics framework for thermal degradation modeling and aging assessment of low-voltage nuclear cables, with particular focus on EPDM terminations. The proposed methodology integrates geometry-aware thermal modeling, thermo-oxidative degradation kinetics, diffusion-limited oxidation effects, property evolution mapping, and nondestructive diagnostic correlation within a unified computational environment. By establishing a closed stress–response–diagnosis–prognosis loop, the framework advances beyond conventional empirical lifetime estimation methods. The results demonstrate that termination-specific thermal modeling is essential for identifying localized hotspots that significantly accelerate aging. Coupling the temperature field with oxidation kinetics and oxygen diffusion enables spatially resolved degradation mapping,

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capturing non-uniform aging behavior across insulation thickness. This approach provides improved realism compared to Arrhenius-based extrapolation and thermal-only simulations, which assume uniform degradation progression. The integration of a diagnostic correlation layer allows degradation severity to be translated into measurable inspection indicators such as insulation resistance decay and dielectric loss growth. The development of a composite health index and remaining useful life estimation further enhances practical applicability for condition-based maintenance and long-term asset management. Overall, the proposed framework provides a scalable and physically interpretable predictive tool for nuclear cable reliability assessment. Its modular MATLAB implementation supports reproducibility and future extension to additional environmental stressors, contributing to improved safety assurance and maintenance planning in nuclear power plant infrastructure.

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