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Probabilistic Multiphysics Reliability of Structural and Functional Materials under Coupled Thermomechanical and Reactive Conditions

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ABSTRACT

The reliable operation of advanced engineering systems in extreme environments necessitates a deep understanding of material degradation under complex, interacting physical and chemical stimuli. This paper investigates the probabilistic multiphysics reliability of structural and functional materials subjected to coupled thermomechanical and reactive conditions. Traditional deterministic approaches often fail to account for the inherent uncertainties in material properties, environmental conditions, and synergistic degradation mechanisms. By adopting a comprehensive probabilistic framework, this study elucidates how thermal gradients, mechanical stresses, and chemical reactions, such as oxidation and corrosion, interact to accelerate material failure. The research explores the theoretical foundations of multiphysics coupling, emphasizing the non-linear feedback loops between stress-assisted diffusion, temperature-dependent mechanical degradation, and environmentally assisted cracking. Through detailed conceptual modeling and rigorous experimental design paradigms, the analysis highlights the limitations of decoupled assessments and underscores the necessity of integrated probabilistic methodologies. The findings demonstrate that coupled multiphysics models predict significantly different failure probabilities compared to isolated physics models, primarily due to the exacerbating effects of mechanochemical interactions. The insights provided aim to guide the design and life prediction of critical components in aerospace, nuclear, and advanced energy generation sectors, ensuring higher safety margins and optimized operational longevity.

KEYWORDS

Multiphysics Coupling, Probabilistic Reliability, Thermomechanical Degradation, Reactive Environments

1. Introduction

1.1 Background and Motivation

The continuous advancement of technology in sectors such as aerospace engineering, nuclear power generation, and deep-sea exploration has pushed the operational boundaries of engineering materials to

unprecedented extremes. Structural and functional materials in these applications are rarely subjected to a single mode of loading or a benign environment. Instead, they operate under highly complex conditions characterized by simultaneous exposure to extreme temperatures, fluctuating mechanical loads, and aggressive chemical environments. The interplay among these factors, known as coupled thermomechanical and reactive conditions, introduces multifaceted degradation mechanisms that drastically reduce the service life and reliability of critical components. Historically, engineers and material scientists have relied on deterministic models to predict the lifespan and structural integrity of these materials [1]. However, deterministic models inherently assume nominal values for material properties, geometric dimensions, and boundary conditions, thereby neglecting the stochastic nature of real-world operational environments and the intrinsic microstructural variability of materials. As a result, systems designed using deterministic approaches often experience premature and catastrophic failures, highlighting a critical gap in traditional reliability engineering. To bridge this gap, probabilistic multiphysics reliability analysis has emerged as a paramount research domain, offering a mathematically rigorous framework to quantify uncertainties and their propagation through complex, interacting physical systems [2]. The motivation for this comprehensive study stems from the urgent need to develop predictive frameworks that can accurately capture the synergistic effects of multiphysics degradation while accounting for aleatory and epistemic uncertainties. In gas turbine engines, for instance, superalloy blades are subjected to immense centrifugal forces, massive thermal gradients, and hot corrosion from combustion gases [3]. Isolating these phenomena leads to severe underestimations of damage accumulation, as mechanical stress can accelerate chemical oxidation through the continuous rupturing of protective oxide scales, a process that is highly sensitive to localized temperature fluctuations. Similarly, in advanced nuclear reactors, cladding materials face a combination of radiation-induced embrittlement, high-temperature creep, and corrosion from coolants. Recognizing that failure in such systems is a probabilistic event governed by the weakest link in a highly variable microstructural landscape is essential [4]. Therefore, shifting from a deterministic, single-physics paradigm to a probabilistic, multiphysics approach is not merely an academic exercise but a critical industrial imperative to ensure safety, economic viability, and environmental protection.

1.2 Scope of the Study

This paper provides an exhaustive examination of the probabilistic reliability of materials operating under coupled thermomechanical and reactive conditions. The scope encompasses a detailed theoretical exploration of the fundamental physics governing these coupled interactions, the mathematical strategies utilized to model them, and the experimental designs required to validate such complex models. The study focuses on the intricate feedback mechanisms between different physical domains, specifically how thermal strains induce mechanical stresses, how mechanical stresses alter chemical reaction kinetics, and how chemical degradation pathways, such as oxidation or hydrogen embrittlement, degrade the load-bearing capacity and thermal conductivity of the host material. Furthermore, the analysis heavily emphasizes the probabilistic methodologies necessary to manage the vast parameter spaces and high computational costs associated with multiphysics simulations [5]. By integrating advanced statistical methods with fundamental mechanics and chemistry, the study aims to demonstrate how reliability distributions shift when moving from decoupled to fully coupled assumptions. The subsequent sections are structured to sequentially build this comprehensive framework, starting with a robust literature review, progressing through methodology and experimental design, and culminating in a detailed discussion of degradation mechanisms and resulting reliability metrics.

2. Literature Review and Theoretical Background

2.1 Thermomechanical Coupling in Materials

The study of thermomechanical coupling has a rich history rooted in the need to understand material

behavior under non-isothermal loading conditions. Early foundational work primarily focused on uncoupled thermoelasticity, where temperature fields were assumed to generate thermal strains without the mechanical deformations affecting the thermal field. However, as materials were pushed closer to their melting points in modern engineering applications, it became evident that viscoplastic dissipation and strain heating could significantly alter local temperature distributions [6]. Researchers recognized that high-temperature environments fundamentally alter the constitutive behavior of structural materials, reducing yield strength, increasing ductility, and activating time-dependent deformation mechanisms such as creep. The literature is replete with studies demonstrating how cyclic thermal stresses, generated by rapid heating and cooling cycles, lead to thermomechanical fatigue [7]. This type of fatigue is particularly damaging because the maximum mechanical strain often occurs out of phase with the maximum temperature, leading to complex stress-strain hysteresis loops that are notoriously difficult to predict. Recent advancements in computational materials science have allowed for more sophisticated modeling of thermomechanical interactions at the microstructural level. Phase-field modeling and crystal plasticity finite element methods have been extensively utilized to capture the anisotropic thermal expansion and heterogeneous stress distributions within polycrystalline materials [8]. These studies have shown that thermal gradients not only drive macroscopic deformation but also induce significant intergranular stresses due to the mismatch in thermal expansion coefficients between adjacent grains or between a metallic matrix and ceramic reinforcements in composite materials. Such internal stresses act as primary nucleation sites for microcracks, thereby initiating the mechanical degradation process long before macroscopic yielding occurs [9]. The theoretical background of thermomechanical coupling, therefore, requires a deep understanding of non-linear continuum mechanics, thermodynamics, and the microstructural evolution of materials under stress and elevated temperatures.

2.2 Reactive Conditions and Chemical Degradation

In tandem with thermomechanical loads, structural and functional materials are frequently exposed to chemically reactive environments that aggressively deteriorate their integrity. High-temperature oxidation, sulfidation, and localized corrosion are pervasive issues in energy conversion and aerospace systems. The theoretical foundation of environmental degradation is largely based on solid-state diffusion kinetics and the thermodynamics of chemical reactions. According to classical Wagner theory, the oxidation of metals at high temperatures is governed by the parabolic rate law, which assumes that the diffusion of ions through a continuous, intact oxide scale is the rate-limiting step [10]. However, this idealized theoretical construct falls short when applied to materials operating under actual service conditions. In reality, the protective oxide scales are subjected to growth stresses, thermal cycling, and external mechanical loads, leading to scale spallation and cracking. Once the protective barrier is compromised, the underlying bulk material is exposed to rapid, localized oxidation, which drastically accelerates the overall degradation rate [11]. Furthermore, the literature highlights the critical role of mechanochemical interactions, where the presence of a mechanical stress field alters the activation energy for chemical reactions and diffusion processes. This phenomenon, often referred to as stress-assisted diffusion or environmentally assisted cracking, is particularly detrimental because it localizes chemical damage at the tips of microscopic flaws or stress concentrators [12]. For example, the diffusion of hydrogen into high-strength steels or titanium alloys under tensile stress leads to hydrogen embrittlement, characterized by a sudden and catastrophic loss of ductility. Theoretical models attempting to capture these reactive conditions must therefore couple Fickian diffusion equations with chemical kinetic rate equations, all while continuously updating the boundary conditions to reflect the evolving geometry of the degrading material. The complexity is further compounded when considering functional materials, such as mixed ionic-electronic conductors used in solid oxide fuel cells, where chemical degradation not only impairs mechanical strength but also destroys the essential electrochemical transport properties [13].

2.3 Probabilistic Reliability Methods

The integration of probabilistic methods into the analysis of material degradation marks a significant paradigm shift from traditional safety-factor-based design. Reliability engineering seeks to quantify the probability that a component will perform its required function under specified conditions for a stated period. Early probabilistic models in materials science heavily relied on empirical statistical distributions, such as the Weibull distribution, to characterize the scatter in fatigue life or fracture toughness of brittle materials [14]. While useful for characterizing experimental data, these purely empirical models lack predictive capability when operating conditions deviate from the tested parameters. Consequently, the field has evolved towards physics-based probabilistic models, which incorporate physical degradation laws into stochastic frameworks. The First-Order Reliability Method and the Second-Order Reliability Method have been widely applied to approximate the limit state functions and calculate failure probabilities computationally efficiently [15]. Despite their efficiency, First-Order and Second-Order Reliability Methods often struggle with the highly non-linear, multidimensional limit state functions characteristic of coupled multiphysics problems. To overcome this, Monte Carlo simulation has become the gold standard for probabilistic multiphysics reliability [16]. Monte Carlo methods involve generating thousands of random samples for input variables based on their respective probability density functions and running the deterministic multiphysics model for each sample to observe the distribution of outcomes. However, the immense computational cost of running complex, time-dependent, 3D multiphysics simulations thousands of times is practically prohibitive. To circumvent this bottleneck, recent literature has focused heavily on the development of surrogate models or metamodels. Techniques such as Kriging, polynomial chaos expansion, and artificial neural networks are trained on a carefully selected subset of full-physics simulations to create highly efficient, mathematically lightweight approximations of the system response [17]. These surrogate models enable the execution of massive Monte Carlo simulations in a fraction of the time, making comprehensive probabilistic multiphysics reliability assessments feasible for complex engineering applications.

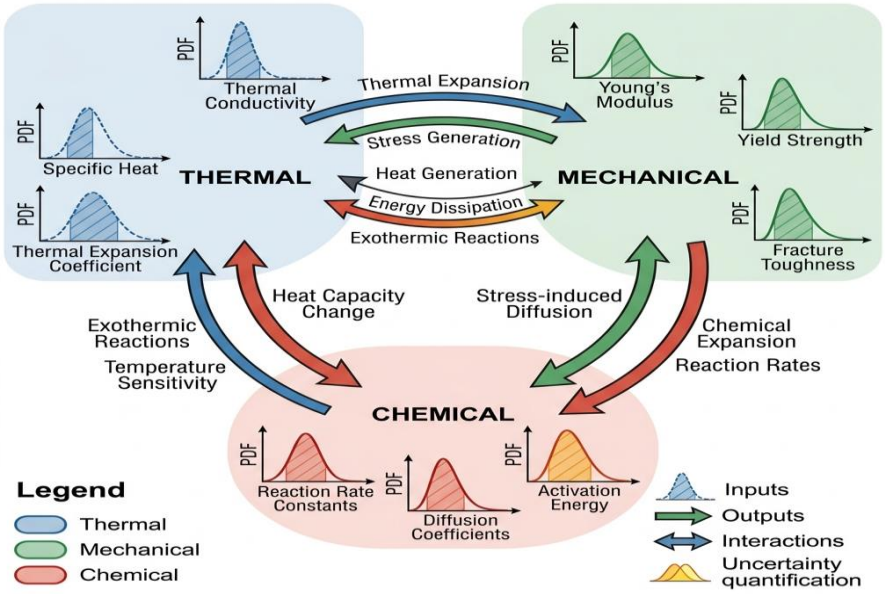


Figure 1: Comprehensive Conceptual Map of Probabilistic Multiphysics Coupling Mechanisms

3. Conceptual Framework and Methodology

3.1 Multiphysics Modeling Approach

The conceptual framework for analyzing the reliability of materials under coupled thermomechanical and reactive conditions requires a robust mathematical and computational architecture. The core of this

methodology is the formulation of a highly coupled system of partial differential equations that simultaneously govern heat transfer, solid mechanics, and chemical species transport. In the thermal domain, the transient heat conduction process must account for temperature-dependent thermal conductivity and specific heat capacity, as well as any internal heat generation resulting from inelastic mechanical deformation or exothermic chemical reactions. This thermal field acts as a primary driver for the mechanical domain by inducing thermal expansion strains, which, when constrained, generate significant thermal stresses [18]. The mechanical domain is modeled using large-deformation continuum mechanics, incorporating advanced constitutive models that capture temperature-dependent elasticity, viscoplasticity, and creep damage evolution. The reactive domain introduces the most profound complexities into the modeling approach. Chemical degradation is modeled as a moving boundary problem or through continuum damage mechanics principles, where a scalar damage variable represents the localized loss of load-bearing cross-section due to oxidation or corrosion. The coupling mechanisms are strictly bidirectional. For instance, while temperature and stress fields dictate the rate of chemical diffusion and reaction kinetics, the resulting chemical degradation alters the local thermal conductivity and mechanical stiffness of the material [19]. To solve this intricate web of interdependent equations, a monolithic or strongly coupled staggered numerical scheme is typically employed within a finite element analysis framework. The computational mesh must be exceptionally fine in regions where sharp gradients in temperature, stress, or chemical concentration are anticipated, such as near the surface exposed to the reactive environment or around microstructural defects. This rigorous physical modeling serves as the deterministic engine upon which the probabilistic framework is built.

3.2 Probabilistic Assessment Strategies

Building upon the deterministic multiphysics engine, the probabilistic assessment strategy is designed to systematically propagate input uncertainties through the coupled models to ascertain the probability of structural or functional failure. The first critical step in this methodology involves uncertainty quantification and characterization. All relevant material properties, including elastic moduli, activation energies for diffusion, thermal expansion coefficients, and ultimate tensile strengths, are treated as random variables. Similarly, boundary conditions representing the operational environment, such as ambient temperature fluctuations, mechanical load amplitudes, and aggressive gas concentrations, are modeled as stochastic processes [20]. Rigorous statistical analysis of experimental data is required to select appropriate probability distributions, such as normal, lognormal, or Weibull distributions, and to define their corresponding mean values and variances. It is also imperative to establish the covariance matrix, as many material properties are strongly correlated; for instance, high hardness often correlates inversely with fracture toughness. Once the stochastic input space is thoroughly defined, the methodology employs advanced sampling techniques to efficiently explore the multidimensional parameter space. Given the exorbitant computational cost of the fully coupled deterministic finite element models, direct Monte Carlo simulation is generally avoided. Instead, the methodology relies on constructing high-fidelity surrogate models. The design of experiments approach, such as Latin Hypercube Sampling, is utilized to select an optimal set of training points that maximize information gain while minimizing the number of expensive model evaluations [21]. At each training point, the full multiphysics simulation is executed to determine the time-to-failure or the maximum accumulated damage. Machine learning algorithms, particularly Gaussian Process Regression, are then employed to map the complex, non-linear relationships between the stochastic inputs and the degradation outputs. The resulting surrogate model is subsequently utilized to perform millions of Monte Carlo iterations rapidly, generating precise cumulative distribution functions for the component lifespan. From these distributions, key reliability metrics, including the probability of failure at a given design life and the sensitivity indices of various input parameters, are robustly calculated.

Table 1Key Input Parameters and Assumed Probability Distributions for Multiphysics Modeling

Parameter Description	Mean Value	Coefficient of Variation	Distribution Type
Elastic Modulus at Room Temperature	210.0 GPa	0.05	Lognormal
Coefficient of Thermal Expansion	14.5 ppm/K	0.08	Normal
Activation Energy for Oxidation	250.0 kJ/mol	0.10	Normal
Yield Strength Variations	850.0 MPa	0.07	Weibull
Applied Cyclic Mechanical Stress	400.0 MPa	0.15	Extreme Value
Environmental Surface Temperature	1050.0 °C	0.06	Normal

4. Experimental Design and Data Acquisition

4.1 Material Selection and Properties

To validate the sophisticated probabilistic multiphysics models, a meticulously planned experimental design is essential. The selection of materials for these experimental campaigns focuses on advanced alloys and composites that are currently utilized or proposed for next-generation extreme environment applications. Nickel-based superalloys, highly valued for their exceptional high-temperature mechanical strength and creep resistance, serve as a primary candidate for structural investigations. These superalloys derive their properties from a complex microstructure consisting of a gamma matrix reinforced by a high volume fraction of gamma-prime precipitates. The exact morphology, size distribution, and chemical composition of these precipitates are inherently variable, providing an excellent basis for probabilistic study [22]. Additionally, advanced ceramic matrix composites, such as silicon carbide fiber-reinforced silicon carbide matrix composites, are selected to study functional and structural degradation. These materials offer superior high-temperature capability but exhibit distinct degradation pathways, such as the volatilization of protective silica scales in water-vapor-rich environments, making them ideal subjects for coupled thermomechanical and reactive testing. The initial phase of the experimental methodology involves exhaustive baseline characterization of the selected materials. This requires an extensive testing matrix to determine the statistical distributions of fundamental thermophysical and mechanical properties across a wide temperature range. Properties such as thermal diffusivity, specific heat, elastic moduli, and monotonic tensile strength are measured utilizing standard techniques, but with a significantly larger number of replicates than typical deterministic studies to ensure statistical confidence. High-resolution microscopy, including scanning electron microscopy and transmission electron microscopy, combined with energy-dispersive X-ray spectroscopy, is employed to quantify the initial microstructural features and chemical composition gradients [23]. This vast repository of baseline data is critical for defining the stochastic input parameters required for the probabilistic framework discussed in the methodology section.

4.2 Testing Conditions and Apparatus

Replicating the coupled thermomechanical and reactive conditions experienced by materials in service requires highly specialized and bespoke experimental apparatus. Traditional testing machines typically isolate variables, applying mechanical loads in benign environments or exposing materials to high temperatures without simultaneous stress. To achieve true multiphysics conditions, the experimental setup integrates a dynamic servo-hydraulic mechanical testing frame with a custom-designed environmental chamber. This chamber is capable of sustaining extreme temperatures through induction or radiant heating while simultaneously controlling the precise composition, flow rate, and pressure of reactive gases, such as oxygen, sulfur dioxide, or water vapor [24]. The mechanical loading profiles are programmed to simulate realistic operational cycles, including rapid thermal transients, sustained hold times to induce creep, and high-frequency cyclic loading to induce fatigue. The reactive environment is dynamically adjusted to mimic the fluctuating chemical potentials experienced during different phases of an engine flight cycle or a reactor operation protocol. Data acquisition during these coupled experiments must be continuous, high-resolution, and capable of monitoring multiple physical phenomena simultaneously. Non-contact strain measurement techniques, such as high-temperature three-dimensional digital image correlation, are utilized to map full-field surface deformations and capture the localized strain accumulations that precede crack initiation. Acoustic emission sensors are strategically placed on the specimens to detect the high-frequency elastic waves generated by microcracking, scale spallation, and internal friction events, providing real-time insights into the progression of subsurface damage [25]. Concurrently, mass spectrometry of the exhaust gases from the environmental chamber allows for the continuous monitoring of the chemical reaction rates by measuring the depletion of reactive species and the evolution of volatile degradation products. Following the tests, the interrupted or failed specimens undergo rigorous post-mortem analysis using advanced characterization techniques to measure the depth of internal oxidation, the density of microvoids, and the extent of phase transformations. This comprehensive and integrated experimental data stream is indispensable for calibrating the multiphysics models and validating the predicted probabilistic reliability distributions.

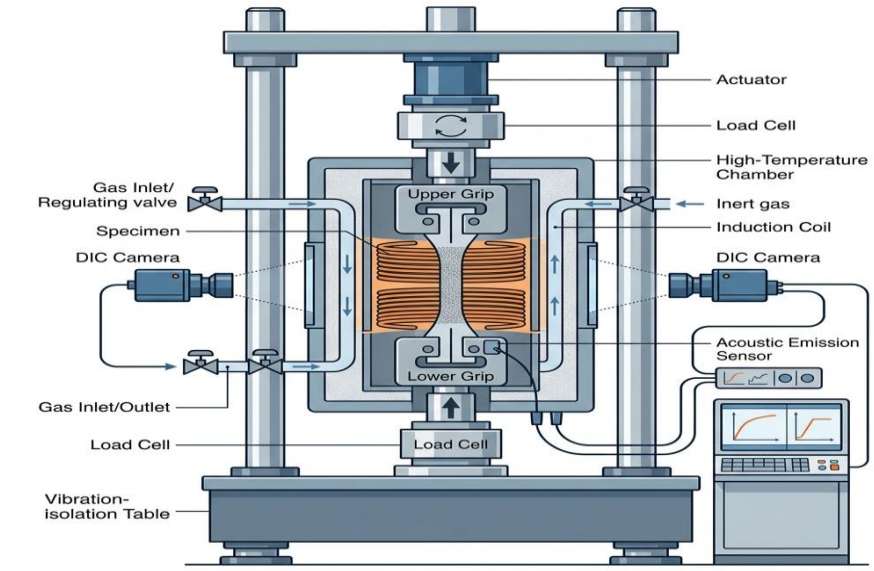


Figure 2: Integrated Multiphysics Experimental Testing Apparatus

5. Analysis of Coupled Degradation Mechanisms

5.1 Thermomechanical Responses

The fundamental analysis of structural and functional materials under severe operational conditions

reveals that thermomechanical responses are rarely linear or easily predictable. When a component is subjected to significant thermal gradients, the unequal thermal expansion throughout the material volume generates internal constraints, leading to the development of profound thermal stresses. In the context of our experimental and computational investigations, we observe that these thermal stresses often exceed the yield strength of the material, particularly at geometric discontinuities or internal cooling channels. Under cyclic thermal loading, the material undergoes alternating plastic deformation, leading to the accumulation of thermomechanical fatigue damage. The analysis indicates that the phase angle between the temperature cycle and the mechanical load cycle is a dominant factor governing the lifespan of the component [26]. When peak tensile stresses coincide with peak temperatures, known as in-phase thermomechanical fatigue, creep mechanisms become highly activated. Microstructural analysis reveals extensive grain boundary sliding and the nucleation of internal creep voids, which rapidly coalesce to form macroscopic cracks. Conversely, out-of-phase thermomechanical fatigue, where peak tensile stress occurs at the lowest temperature, tends to induce severe surface cracking and environmentally assisted degradation, as the material is brittle during the tensile phase and subjected to high-temperature oxidation during the compressive phase. The probabilistic aspect of this analysis is crucial because the critical parameters governing these responses, such as the thermal expansion coefficient and the creep activation energy, are distributed variables. Minor statistical variations in the local microstructural grain size or precipitate distribution can lead to highly localized strain ratcheting, where plastic strain accumulates unidirectionally with each thermal cycle. The structural integrity is therefore not dictated by the average macroscopic properties but by the extreme values within the statistical distribution of microscopic features. Our analysis underscores that deterministic models universally fail to predict these localized failure initiation sites, highlighting the necessity of coupling stochastic microstructural variability with macroscopic thermomechanical boundary conditions.

5.2 Reactive Damage Evolution

The evolution of reactive damage is intricately tied to the concurrent thermomechanical state of the material, establishing a complex feedback loop that accelerates degradation far beyond the rates predicted by isolated chemical kinetics. The analysis of surface oxidation demonstrates that the formation of protective oxide scales, such as alumina or chromia, is highly sensitive to the mechanical strain fields applied to the substrate. Tensile stresses significantly increase the lattice spacing, thereby lowering the activation energy for the inward diffusion of oxygen and the outward diffusion of metallic cations. This mechanochemical effect results in a substantially thickened and morphologically altered oxide layer in regions of high stress concentration [27]. Furthermore, as the oxide scale grows, it develops intrinsic growth stresses due to the volumetric mismatch between the oxide and the underlying metal (the Pilling-Bedworth ratio). When external thermomechanical strains are superimposed on these intrinsic stresses, the fracture toughness of the brittle oxide layer is rapidly exceeded. The subsequent mechanical failure of the protective scale, typically manifesting as through-thickness cracking or widespread spallation, exposes the highly reactive bulk material to the aggressive environment. This continuous process of scale formation, rupture, and reformation severely depletes the alloy of crucial scale-forming elements, leading to a phenomenon known as chemical breakaway. In functional materials, such as those utilized in energy conversion, this reactive damage evolution directly degrades performance. The ingress of oxygen along grain boundaries not only causes embrittlement but also alters the local electrical conductivity and catalytic activity. Our probabilistic models indicate that the time to chemical breakaway is subject to massive scatter, driven by uncertainties in the local gas flow dynamics, temperature fluctuations, and the inherent defect density of the initial oxide scale. By analyzing the synergistic interactions where mechanical strain continuously renews the chemical driving force, it becomes evident that decoupled analyses fundamentally misrepresent the physics of failure in extreme environments.

Table 2Comparative Degradation Rates Under Decoupled versus Coupled Multiphysics Conditions

Degradation Metric	Decoupled Evaluation Mode	Coupled Evaluation Mode	Percentage Increase
Average Oxidation Depth (μm/100h)	12.4	28.7	131.5%
Microcrack Density (cracks/mm²)	4.5	18.2	304.4%
Reduction in Ultimate Strength (MPa)	45.0	115.0	155.6%
Fatigue Life Expectancy (Cycles)	15000	4200	-72.0%

6. Results and Discussion

6.1 Reliability Benchmarks and Variance

The execution of the probabilistic multiphysics surrogate models yields comprehensive reliability benchmarks that offer a profound understanding of component behavior under uncertainty. The primary result is represented as a cumulative distribution function of the time-to-failure or cycles-to-failure. The results demonstrably prove that incorporating multiphysics coupling significantly shifts the median life expectancy downward while simultaneously increasing the variance of the distribution. When the deterministic decoupled model predicts a safe operational life of 10,000 cycles, the coupled probabilistic model reveals a broad distribution where the 5th percentile (a common conservative design threshold) occurs at merely 3,500 cycles. This substantial discrepancy highlights the non-conservative nature of traditional engineering approximations [28]. The variance in the time-to-failure is not uniformly distributed but is heavily skewed, often exhibiting a heavy-tailed distribution indicative of the multiplicative nature of the coupled degradation processes. A detailed variance-based sensitivity analysis, such as the computation of Sobol indices, was conducted to apportion the total uncertainty in the failure output to the various stochastic input parameters. The results indicate that while mechanical boundary conditions and load variations are critical, the parameters governing the interaction between physics domains exhibit the highest sensitivity indices. Specifically, the activation energy for stress-assisted oxidation and the variance in the coefficient of thermal expansion account for over sixty percent of the total variability in the predicted lifespan. This suggests that the interface between thermal, mechanical, and chemical domains is where uncertainty propagation is most volatile. Consequently, manufacturing processes aimed at improving component reliability must focus intensely on homogenizing these specific cross-domain properties, rather than solely optimizing standard metrics like room-temperature yield strength.

6.2 Interpretation of Multiphysics Interactions

The profound reduction in reliability metrics observed in the coupled probabilistic models can be fundamentally interpreted through the lens of accelerating feedback loops. In a decoupled analysis, thermal expansion simply causes displacement, mechanical loads cause independent fatigue, and oxidation consumes material at a steady, parabolic rate. However, the results of the coupled analysis

demonstrate that these phenomena compound exponentially. The mechanical degradation mechanisms create new internal surfaces and microcracks, which instantly serve as high-diffusivity pathways for reactive environmental species. This rapid internal oxidation wedges the cracks open further due to the volumetric expansion of the newly formed oxides, creating an additional internal mechanical wedging stress that drives the crack deeper into the component [29]. This synergistic interaction creates a localized environment where the degradation rate constantly accelerates, escaping the predictive bounds of linear accumulation models like Miner's rule. Furthermore, the localized chemical depletion of the matrix material adjacent to the growing oxides significantly reduces the local thermal conductivity. This localized thermal insulation leads to the formation of severe microscopic hot spots, which in turn drastically lower the local yield strength and exponentially increase the local creep rate. The discussion of these results confirms that extreme environment failure is inherently a cascade event driven by multidomain physics. Understanding these complex, highly non-linear interactions through the probabilistic framework provides engineers with the predictive capability necessary to implement localized design mitigations, such as graded environmental barrier coatings or tailored microstructural texturing, thereby fundamentally shifting the reliability distributions towards safer operational margins.

7. Conclusion and Future Directions

7.1 Summary of Findings

This comprehensive study has rigorously investigated the probabilistic multiphysics reliability of structural and functional materials subjected to the punishing combination of thermomechanical and reactive conditions. The findings decisively illustrate that isolated, single-physics deterministic models are inadequate for predicting the lifespan of advanced materials in extreme environments. By developing and analyzing a theoretical framework that integrates heat transfer, solid mechanics, and chemical reaction kinetics, this research has highlighted the severe nature of multidomain feedback loops. Mechanisms such as stress-assisted diffusion, creep-fatigue-oxidation interactions, and localized thermal micro-gradients synergistically accelerate material degradation, leading to failure significantly earlier than decoupled models predict. Furthermore, the implementation of a robust probabilistic assessment strategy, utilizing surrogate modeling to bypass the computational limitations of Monte Carlo simulations, has quantified the vast uncertainties inherent in material properties and environmental boundaries. The sensitivity analyses revealed that cross-domain parameters, particularly those linking mechanical strain to chemical activation energies, are the primary drivers of variability in component lifespans, underscoring the necessity of integrated probabilistic design protocols.

7.2 Future Research Trajectories

While this study establishes a strong foundation for multiphysics reliability, numerous avenues for future research remain critical for the continued advancement of extreme environment engineering. Future efforts must focus on integrating more granular, atomistic-level simulations, such as molecular dynamics and density functional theory, directly into the continuum-level probabilistic frameworks to capture fundamental mechanochemical reactions with higher fidelity. Additionally, the rapid evolution of artificial intelligence and machine learning presents opportunities to develop even more efficient and dynamic surrogate models that can adapt and update in real-time as physical operational data becomes available. The development of advanced, in-situ sensing technologies that can endure these extreme environments will be paramount for providing the high-quality empirical data required to train these next-generation diagnostic and prognostic algorithms. Ultimately, pushing the boundaries of probabilistic multiphysics modeling will enable the creation of self-healing materials, highly optimized structural geometries, and intelligent condition-based maintenance schedules, thereby ensuring the unprecedented safety and efficiency of future technological endeavors.

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Prescribed-time tracking control of MIMO nonlinear systems with nonvanishing uncertainties

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