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# ENTROPY-BASED MECHANICS MODELING FOR RPV EMBRITTLEMENT OVER EXTENDED OPERATIONAL LIFETIMES

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## ABSTRACT

This study introduces an innovative entropy-based materials mechanics modeling framework to address reactor pressure vessel (RPV) embrittlement in nuclear power reactors. The model leverages strain entropy to capture three fundamental processes in RPVs: electron-electron interactions ($S_1$) governed by Coulomb's equation, electron-phonon interactions ($S_2$) associated with lattice distortions, and phonon-phonon interactions ($S_3$) driving bond breakdown and plastic deformation. These entropy contributions ($S_1$–$S_3$) are integrated into a Macroscopic and Multiphysics Mechanics Equation based on entropy evolution, establishing a nonlinear strain-entropy relationship that provides a unified understanding of material behavior in reactor environments. This framework enables precise evaluation of radiation-induced hardening in RPV steel over extended operational lifetimes. Using an optimized cubic trinomial function of entropy, it models nonlinear hardening effects over 80-year reactor lifespans, extending beyond experimental constraints by incorporating physical insights from OWAY models. Additionally, the approach allows calibration with diverse nuclear plant operational datasets, offering significant potential to enhance safety measures and extend the service life of nuclear facilities. Beyond nuclear applications, the developed equation is also applied to characterize Friedmann's Scale of Universe and Time relationship, introducing new perspectives in cosmological exploration. This interdisciplinary approach bridges materials science and astrophysics, highlighting entropy's fundamental role in both reactor safety and the broader understanding of the universe's evolution.

## KEYWORDS

Entropy-driven stress modeling, RPV embrittlement mechanisms, Radiation-induced hardening, Nuclear power plant lifespan prediction, Entropy-driven cosmology.

## INTRODUCTION AND BACKGROUND

Reactor pressure vessel (RPV) embrittlement is a significant challenge for the long-term safety and reliability of nuclear power reactors(Odette * et al. 2006). As primary containment structures, RPVs operate under extreme conditions, including high radiation flux, temperature variations, and mechanical stresses. Over time, these factors lead to microstructural changes such as radiation-induced hardening and embrittlement(Lee et al. 2023), compromising structural integrity(Odette et al. 2019). Addressing these challenges requires advanced modeling approaches that account for complex, nonlinear material interactions(Liu et al. 2022).

With nuclear power plants operating for up to 80 years, accurate predictive models are essential for safety management and lifecycle optimization. Traditional embrittlement models provide valuable insights but often fail to capture the nonlinear interactions occurring across multiple scales. This study introduces an entropy-based materials mechanics framework that integrates fundamental physical principles to enhance predictive capabilities.

The framework leverages strain entropy contributions from electron-electron ($S_1$), electron-phonon ($S_2$), and phonon-phonon ($S_3$) interactions, which influence radiation-induced changes in RPV steel. By incorporating these entropy contributions, the model quantifies material nonlinearity over time, offering deeper insights into radiation-induced mechanical behavior. A key advancement of this study is the introduction of a Macroscopic and Multiphysics Mechanics Equation rooted in entropy evolution, establishing a nonlinear stress-entropy relationship for evaluating radiation-induced hardening and modeling nonlinear hardening over extended operational lifetimes.

### *Nonlinear Hardening Resulting From Radiation-induced Embrittlement*

Radiation exposure alters RPV mechanical properties, transitioning materials from ductile to brittle behavior, which affects operational temperature thresholds and fracture resistance(Liu et al. 2022). Accurately predicting these changes is essential for reactor integrity and effective maintenance planning. This study introduces an entropy-based framework that quantifies the nonlinear evolution of mechanical strength over an 80-year operational period. By integrating entropy contributions from electron-electron ($S_1$), electron-phonon ($S_2$), and phonon-phonon ($S_3$) interactions(Tan et al. 2022), the model enhances predictions of radiation-induced hardening and informs long-term safety strategies.

### *The Exploration Of Nonlinearity And Entropy Across Space And Time Scales*

Building on the understanding of nonlinear hardening in RPVs, this study extends the exploration of nonlinearity and entropy across diverse spatial and temporal scales. Despite extensive efforts to develop a Multiphysics entropy-based Young's equation(Shu et al. 2015; Wu et al. 2020; Wu et al. 2023; Wu and Wu 2021), challenges remain in integrating Multiphysics principles and scaling factors effectively. A more comprehensive equation is needed to capture nonlinear interactions across multiple physical domains.

Entropy governs material behavior across disciplines, from materials science to astrophysics and cosmology. This study examines entropy's role in deviations from direct responses to applied stimuli, with applications in stress-strain relationships of radiation-exposed RPVs and the scale-time relationship in Friedmann's past and future model of the universe(Vakili and Khosravi 2012). A universally applicable equation is essential for modeling nonlinear behavior across scales. This study introduces an entropy-based methodology grounded in thermodynamic principles to establish a robust framework for understanding material responses. By integrating chemical, thermal, mechanical, electrical, and magnetic factors, this approach ensures thermodynamic consistency and enables accurate predictions for systems from the nanoscale to bulk materials.

Additionally, this research presents entropy as a mathematical metric for quantifying dynamic convergence processes, represented through configuration entropy in specific spatial or temporal distributions. Refining and validating this approach is crucial for its broad applicability in materials design, engineering, energy, and healthcare. This study focuses on developing an entropy-based Young's equation and addressing nonlinearities in entropy and strain equations while investigating entropy's role in mitigating radiation-induced embrittlement in RPV steels over extended operational lifetimes.

By bridging materials science and cosmology through an entropy-based framework, this interdisciplinary approach has the potential to revolutionize industries, drive scientific innovation, and open new pathways for understanding nonlinear behavior across a wide range of fields.

# METHODOLOGY

***Developing A Macroscopic And Multiphysics Strain Equation Grounded In The Evolution Of Entropy***

Incorporating the concept of entropy into mechanical strain via the Young's equation, which governs the stress-strain relationship begins with an exploration of the interplay between entropy and strain. Leveraging this groundwork, we derive the entropy-based Multiphysics Young's Equation at macroscopic scales via a first-principles approach. Kimball's study(Kimball 1931) initially established a linear equation that precisely relates entropy to strain, where entropy (S) for an ideal gas phase was computed as the product of the Boltzmann constant ($K_B$) and the overall strain (ε) in the system, or $S=K_B\ \varepsilon$. However, for non-ideal solid/liquid solutions, these principles governing ideal gas phases do not apply. As a result, the conventional ideal solution model used for gas phases is inadequate in accurately determining the strain arising from entropy in an air-liquid-solid system. To overcome this limitation, novel nonlinearity relationships between entropy and strain are required, particularly when dealing with systems that deviate from ideal solution assumptions. Our research expands upon the author's prior work, which involved the development of entropy equations as functions of stress σ (Equation 1.0a) and strain ε (Equation 1.0b),

$$\sigma_F - \sigma_0 = f(S_F, S_0) \tag{1.0a}$$

$$\mathcal{E}_F - \mathcal{E}_0 = g(S_F, S_0) \tag{1.0b}$$

in real-world gas-liquid-solid systems, where the subscript F and 0 represent respectively its final and initial process stage, originally conceived during the investigation of liquid wetting theory and experiments. In this context, the contact angle of a sessile liquid droplet on a solid surface is determined by three shear stresses: solid-liquid $\gamma_{SL}$, liquid-vapor $\gamma_{LV}$, and solid-vapor $\gamma_{SV}$, as observed in Young's equation $\gamma_{LV}\cos\theta = \gamma_{SV} - \gamma_{SL}$ (Villa et al. 2018), where shear strain (ε) is represented from the water contact angle θ. By employing liquid wetting analysis(Tan et al. 2022; Wu et al. 2020; Wu and Wu 2017), we have effectively constructed a theoretical framework and formulated an equation that clarifies the relationship between strain, denoted by the change in water contact angle (from the initial $\theta_o$ to $\theta_F$), and the entropy change (from $S_o$ to $S_F$) in a typical air-liquid-solid system where $\theta_F$ is less than 90° when subjected to an external magnetic field (H).

$$S_0 = -W\left(\frac{2}{(1+cos\,\theta_0)} - cos\,\theta_0\right)_{for\ H=0} \tag{1.1a}$$

$$S_F = -W\left(\frac{2}{(1+\cos\theta_F)} - cos\,\theta_F\right)_{for\ H=H\_applied} \tag{1.1b}$$

Here, $W = \gamma\pi r^2/\mathrm{T}$, where θ, γ, and T represent the equilibrium contact angle, the liquid surface free energy, and temperature, respectively.

Therefore,

$$S_F - S_0 = -W\left(\frac{2}{(1+cos\,\theta_F)} - cos\,\theta_F\right) + W\left(\frac{2}{(1+\cos\theta_0)} - cos\,\theta_0\right)$$

$$S_F - S_0 = f(\theta_F, \theta_0)\,(-W) \tag{1.1c}$$

Equations 1.1a, 1.1b and 1.1c are the entropy-based Young's equation, revealing the shear strain (ε or θ) as a function of entropy ($S_F - S_0 = f(\theta_F, \theta_0)\,(-W)$), which depends on alterations in contact angles.

This equation formulates system entropy as a function of the cosine of the contact angle, considering the influences of external magnetic fields, denoted as H (for non-zero field) or Ho (for zero field). Moreover, the entropy-based Young's equation developed in this study considers the influence of external mechanical loadings, as suggested by existing literature, which indicates that it is possible to manipulate a solid's surface entropy by applying mechanical loads that affect surface electron density(Friedman et al. 2013). Upon exposure to a mild applied strain field within the elastic range of the solid, the material undergoes a reversible deformation known as elastic deformation. Throughout this stage, the relationship between the applied load and the consequent strain remains linear. Nevertheless, surpassing the yield point threshold leads the solid material into the domain of plastic deformation. In this phase, plastic deformation involves the permanent rearrangement of destabilized atoms within a disordered crystal structure, often yielding defects or metastable polymorphic forms, aimed at minimizing the overall system energy. Additionally, our research employs the Born-Oppenheimer approximation theory, treating electronic, nuclear, electron-phonon, and phonon-phonon coupling interactions as independent factors to isolate the sources of strain entropy within a solid(Tan et al. 2022). The primary source of strain entropy ($S_1$) originates from electron-electron interactions, as described by Coulomb's equation. The second source ($S_2$) arises from electron-phonon interactions involving lattice distortions and electrons. The third source ($S_3$) of strain entropy emerges from lattice vibrations induced by phonon-phonon interactions. The activation of phonon-phonon interactions results in bond breakdown and subsequent plastic deformation. As a result, we have established the non-linear strain entropy relationship as follows(Tan et al. 2022):

$$\Delta S_W = \frac{1}{T}\left(\frac{E_0+(1-\nu)M\varepsilon}{2}\varepsilon^2 - \frac{A_0}{r_i}\varepsilon\right) \tag{1.2a}$$

In the above, M represents the alterations in phonon-phonon coupling entropy induced by biaxial loading, while $\Delta S_W$ encompasses the comprehensive strain entropy changes, including those associated with $S_1$, $S_2$, and $S_3$ at each atomistic event. The variables Temperature (T), Young's modulus (Eo), Poisson ratio (ν), constant of Coulomb potential (Ao), and strain (ε) are denoted as such. Additionally, it's worth noting that the linear component of Equation 1.2a ($\frac{A_0}{r_i}\varepsilon$) aligns with Kimball's findings for a gas phase. Notably, the square and cubic strain components in Equation 1.2a are of particular significance, as 3D crystal solid solutions deviate from ideal solution behavior, a departure from the characteristics of a gas phase. Incorporating a comprehensive range of Multiphysics factors, including not only magnetic and mechanical but also chemical, thermal, and electrical loadings, into the entropy-based Young's equation has been accomplished by the author, as demonstrated in his work on chemical, thermal, and electrical models(Lee et al. 2023). This achievement marks the development of a truly Multiphysics-oriented entropy-based Young's equation for macroscopic systems. The next step is to compute the RPV embrittlement stress σ using the entropy contributions from $S_1$, $S_2$, and $S_3$.

For the left side of Equation (1.2a), we apply the relation $S_F - S_0 = \sigma$, derived from Equation (1.1.c) by defining $f(\theta_F,\theta_0)(-W) = \Delta\sigma$ in Equation (1.1c).

For the right side of Equation (1.2a), we express σ as a nonlinear function of strain $\varepsilon$:

$$\Delta\sigma = A_i\,\varepsilon + B_i\,\varepsilon^2 + C_i\,\varepsilon^3 \quad (1.2b)$$

where $A_i$, $B_i$, and $C_i$ (i=1,2) are constants to be optimized based on experimental measurements.

Applying Kimball's linear entropy-to-strain approach, we replace $\varepsilon$ with the entropy of mixing in an ideal solution ($\Delta S_i$), where $S_1 = \Delta S_i = \varepsilon$, $S_2 = \varepsilon^2$, and $S_3 = \varepsilon^3$. This leads to the reformulated expression:

$$\Delta\sigma = A\,\Delta S_i + B\,\Delta S_i^2 + C\,\Delta S_i^3 \quad (1.2c)$$

Equation (1.2c) bridges entropy and mechanical stress, providing a robust foundation for evaluating RPV embrittlement through an entropy-based mechanics framework.

***Applying Kimball's entropy-strain approach to extend Young's Equation across multiple scales***

RPV embrittlement process involves entropy changes across multiple scales. Exploring nanoscale entropy unveils a realm of opportunities not only in RPV embrittlement study but also in materials science, extending beyond the mere scaling down of macroscopic entropy. It delves into a domain where quantum intricacies, surface phenomena, and statistical fluctuations intricately shape nonlinear material responses(Kim et al. 2023). These nuanced adjustments exert influence on properties such as melting points, electrical conductivity, and strength, enabling tailored material design with applications spanning nanotechnology, biomedicine, and energy storage. This journey effectively bridges the micro to macro scales, facilitating precise control through entropy-based Young's equations to drive innovative solutions. The incorporation of scale based entropy into our understanding as in Equation 1.0a and 1.0b, proves pivotal for predicting and manipulating nanomaterial behavior, propelling advanced material development across diverse fields, from technology to medicine. Overcoming challenges such as accurate measurements and quantum effects is paramount for scientific progress, particularly in the nanoscale, where the assembly of multiple nanostructures collectively gives rise to distinctive nonlinearities in physical properties. This paper expands on the pioneering work by (Wu et al. 2023), which employed entropy to elucidate the collective dynamic behaviors of nanostructures. In particular, the method utilized here involves configurational entropy of mixing ($\Delta S_i$) across time scales of nuclear power plant life span period, which is detailed by the following formula:

$$\Delta S_i = -M\left(\frac{\varphi t_t}{\varphi t_0}\right) ln\left(\frac{\varphi t_t}{\varphi t_0}\right) - M\left(1 - \frac{\varphi t_t}{\varphi t_0}\right) ln\left(1 - \frac{\varphi t_t}{\varphi t_0}\right) \quad (1.2d)$$

Where $\varphi t_t$ and $\varphi t_0$ is respectively the fluence at reference $t_0$ and real-time $t_t$, and M has the same definition as in Equation 1.2a.

$$\Delta\sigma = A\,\Delta S_i + B\,\Delta S_i^2 + C\,\Delta S_i^3 \quad (1.2e)$$

This approach unveils the crucial role of configurational entropy in time scale elucidating the non-linear relationship between radiation time and entropy of mixing across the lifespan of power plants. According to Equation 1.2e, $\Delta\sigma$ exhibits variation in three distinct zones of radiation time:

a. $\Delta\sigma$ linearly increases with an increase in time space entropy $\Delta S_i$.
b. $\Delta\sigma$ reaches a plateau stage for intermediate-radiation time.
c. $\Delta\sigma$ sharply increases with further radiation time.

These tendencies also align with the patterns delineated in the scale and time relationship based on the Friedmann's Scale of Universe and Time relationship, introducing new perspectives in cosmological exploration, which will be briefly addressed in the discussion section.

# RESULTS AND DISCUSSIONS

### *Nonlinear Hardening Resulting from Radiation-Induced Embrittlement in RPVs Across 80-Year Operational Lifespans*

Understanding the nonlinear radiation-induced hardening(Lee et al. 2023) of Reactor Pressure Vessels (RPVs)(Liu et al. 2022) is crucial for nuclear safety in power plants. We start by employing equation 1.2e to scrutinize the observed data patterns pertaining to irradiation hardening ($\Delta\sigma$) concerning concurrent fluences ($\varphi t$), as detailed in reference(Odette * et al. 2006). Subsequently, we will employ equation 1.0b to establish a predictive model for $\Delta\sigma$ as a function of $\varphi t$, spanning the range from 1017 to 1021 n/cm$^2$ (encompassing a time frame exceeding 80 years of nuclear power plant service), effectively bridging the divide between macro and nano scales. Accurately predicting neutron-induced embrittlement in RPV steels is vital for extending nuclear reactor lifespan. However, extrapolating current irradiation hardening models to high fluence levels, around 1020 neutrons per square centimeter (n/cm$^2$), is essential for extended reactor longevity. Neutron flux significantly affects $\Delta\sigma y$, with thermally unstable irradiation-induced unstable matrix defects (UMD) playing a role. UMD impacts material hardening while serving as defect sinks, affecting stable matrix features (SMF) and copper-rich precipitates (CRP) hardening features by diminishing radiation-enhanced diffusion (RED) efficiency. Robust hardening models are crucial for low flux and high fluences conditions, such as extended vessel life. Materials structures that harden under irradiation include nano-scale Cu-enriched precipitates, SMF, UMD, and late-blooming Mn-Ni-Si-rich precipitate phases (LBP). Two or three-feature models aim to understand interactions affecting hardening. A low-flux, two-feature solute trap-enhanced recombination model (2FM) addresses neutron flux effects with a rate theory framework. For high flux levels, a three-feature model (3FM) considers UMD, SMF, and CRP. Recent enhancements increase model accuracy for low to intermediate flux conditions, improving reliability in predicting reactor life extension. In this research, the unirradiated RPV steel serves as a reference. Entropy reduction, denoted as $\Delta SE$, results from the transformation of RPV steel into a structure with ordered nanostructures. This reduction is assessed using the entropy of resilience7 and is expected to increase hardness compared to the pre-radiation state. A partial reduction in entropy is also anticipated. The $\Delta\sigma$ data in the literature will be bounded by equations 1.2b. The effectiveness of these equations, their comparisons to existing models, and their alignment with experimental data will be examined in the subsequent section.

In their study published in (Odette * et al. 2006) and updated in (Odette et al. 2019), ODETTE et al. delved into the effects of neutron flux ($\varphi$) on irradiation hardening ($\Delta\sigma$) and embrittlement in reactor pressure vessel (RPV) steels, an unresolved and crucial concern. They conducted a comprehensive assessment of neutron flux impacts using a substantial database they developed for RPV steels, subjecting these materials to irradiation at 290°C within three distinct fluences ($\varphi t$)-regimes, spanning a wide range of overlapping fluences ($\varphi t$). Their research revealed an increase in the role of copper-rich precipitates (CRPs) in $\Delta\sigma$, leading to a plateau hardening effect that primarily depended on the copper (Cu), nickel (Ni), and manganese (Mn) content of the alloy, with relative independence from $\varphi$. Notably, the pre-plateau region shifted toward higher $\varphi t$ values with rising neutron flux. The proposed model aligned with a mechanism governed by the recombination rate of vacancies and self-interstitial atoms (SIAs). The analysis of $\Delta\sigma$ data incorporated a comprehensive model that considered several factors, including the excess vacancy concentration, radiation-enhanced copper diffusion coefficient (D*), and the contribution of CRPs to $\Delta\sigma$. Despite elevated recombination rates, radiation-enhanced copper diffusion (RED) exhibited impressive efficiency, with D* values surpassing predictions from simple rate theory models by over 60 times. The

study explored potential explanations for these heightened diffusion rates, including the influence of significant vacancy-solute binding energies that affect vacancy concentrations and jump frequencies near solutes, thereby enhancing both diffusion and recombination processes. The Odette-Wells-Almirall-Yamamoto (OWAY) model, while entirely data-driven and easily assessed, rests on a robust physical foundation that aligns with comprehensive physical models. Nevertheless, its development demanded significant human effort and an in-depth understanding of physical principles, with a relatively specific range of applicability. Additionally, Liu et al.(Liu et al. 2022) demonstrated the use of machine learning models for predicting irradiation hardening under low flux, high fluence, and extended life conditions, contingent upon the quality of the employed databases. As a result, there remains inherent potential for improvements in terms of development speed, flexibility, and adaptability when validating entropy-based Young's equation hardening models. These models encompass aspects considered by OWAY models and venture into uncharted territories, all guided by the principles of thermodynamics across scales, spanning from the macroscale to the nanoscale.

Our initial strategy entails employing entropy to examine the discernible patterns in the $\Delta\sigma$ - $\varphi t$ plots, associated with the resultant precipitate volume fraction (f) as introduced by Odette. Consequently, $\varphi t$ can be used to calculate entropy. Therefore, a $\Delta\sigma$ - $\varphi t$ plot can be elucidated by the underlying physics of a $\Delta\sigma$ - Entropy equation, where the embrittlement of RPVs is a nonlinear function of the generated entropy across temporal space up till 80 years.

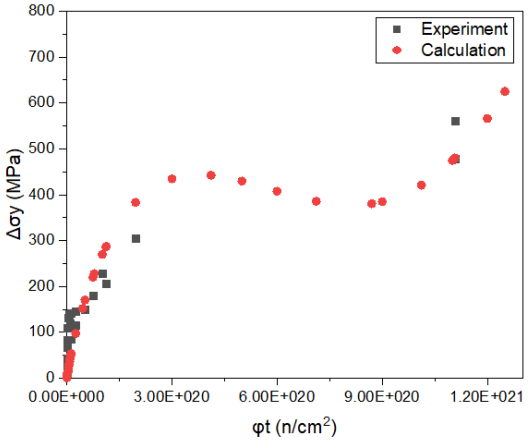


Figure 1: Comparative Analysis of Experimental (in black) and Calculated (in red) Irradiation Hardening Across Concurrent Fluences for RPV alloy LI (0.2Cu, 0.8Ni, 1.4Mn).

On this timeline, entropy is computed using Equation (1.2d). Optimization leads to the derivation of the following equation:

$$\Delta\sigma = 6.5\ S_1 - 0.03\ S_2 + 4.18\times10^{-5}\ S_3 \qquad (1.2f)$$

In Figure 1, three distinct zones are evident: $Z_1$, characterized by an approximate linear increase in $\Delta\sigma$ with $\varphi t$ (ranging from 1017 to 1020 n/cm$^2$); $Z_2$, fluctuating both above and below a plateau in $\Delta\sigma$ (spanning from 1020 to 1021 n/cm$^2$); and $Z_3$, marked by a steady rise in $\Delta\sigma$ with $\varphi t$ (extending from 1021 n/cm$_2$). Notably, these three zones may correspond to those outlined in equation 1.2a, where $S_1$, $S_2$, and $S_3$ become predominant. Equation 1.2f potentially represents entropy changes from physical features in OWAY models and may extend beyond their experimental limits. Nanostructures formed via $\varphi t$ irradiation significantly impact the $\Delta\sigma$ - $\varphi t$ graph. Within zone $Z_1$, the parameter f stabilizes at approximately 0.2.

Contrastingly, in $Z_2$, it steadily increases to 1.5 in a linear manner. Zone $Z_3$ lacks a recorded f value but is expected to demonstrate a sharp incline. Equation 1.2d can effectively characterize this pattern as shown in Figure 1, by utilizing the variables $d_o$, representing the maximum experiment or design fluence, and dt, denoting the fluence measured at time t. The 3-term Equation 1.2e's remarkable ability to replicate the nonlinear behavior observed in RPV embrittlement after 80 years of nuclear power plant operation, rooted in fundamental principles, is fascinating. Consequently, operating within $Z_1$ and $Z_2$ (up to 70 years) is deemed safe, but exercising extra caution in $Z_3$ (or as it approaches 80 years) is advised, as indicated by the rapid escalation seen in the $\Delta\sigma$ - $\varphi$t graph in Figure 1. To interpret the characteristic peak (maximum) and valley (minimum) observed in Figure 1, we propose a dual-entropy framework grounded in thermodynamic principles. This approach introduces two complementary measures: structural (space) entropy, which quantifies the degree of internal order within the material from atomic to macroscopic scales, and time entropy, which captures the temporal coherence or dispersion of structural evolution. The local maximum of hardening peak corresponds to a mechanically responsive phase marked by reduced time entropy — a temporally concentrated and ordered event such as rapid hardening or phase adjustment. This occurs alongside a decrease in structural entropy, reflecting the emergence of more ordered internal configurations and a transition to a constrained structural state. Conversely, the valley or local minimum represents a period of increased time entropy, where structural changes occur more diffusely over time. This is paralleled by an increase in structural entropy, indicative of relaxation, redistribution, or softening processes. While a full theoretical development of this dual-entropy model is underway, the present interpretation offers a thermodynamically consistent explanation of the observed strain–time behaviour and lays the foundation for a new physical understanding of time-dependent material response. This achievement also paves the way for fresh prospects in fine-tuning Equation 1.2e through the utilization of diverse nuclear plant operation databases. Such calibration holds promise for enhancing safety measures and managing the lifespan of these facilities.

It is noteworthy that there is room for improvement in achieving closer agreement between the experimental and calculated values, evident in Fig 1. This discrepancy is expected since the current approach, entropy, only incorporates configuration entropy during the dynamic convergence process. Introducing a non-configurational excess entropy term(Wu and Pelton 1992) in Equation 1.2d can resolve this issue. However, it is essential to highlight that the primary aim of this study is not to precisely replicate experimental data (i.e., $\Delta\sigma$ in Fig 1), but rather, to uncover the fundamental nonlinear principles of Multiphysics across various scales in time and space. For those seeking high-quality optimization, the application of Calphad techniques(Wu and Pelton 1992) could be of interest.

***Entropy explanation on the Friedmann's Scale of Universe and Time relationship***

This study also provides an opportunity to offer new insights into the transitions between different phases of the universe's evolution, as described by the Friedmann equations(Peebles and Ratra 2003), and their potential analogy to entropy-driven engineered systems like nuclear power plants and strain engineering.

The Friedmann equations(Ellis et al. 2003; Peebles and Ratra 2003) have long served as the foundation for understanding the universe's expansion and evolution, linking the scale factor, matter, radiation, and dark energy. The space-time curve in Friedmann's model illustrates the transitions between radiation-dominated, matter-dominated, and dark energy-dominated phases of the universe. These phases are governed by distinct energy densities and corresponding entropy dynamics, transitioning from linear growth (radiation domination) to a plateau (matter domination) and culminating in a sharp exponential rise (dark energy domination). The current phase, influenced predominantly by dark energy ($\Omega\Lambda \approx 0.7$), aligns with the observed accelerated expansion of the universe. In Friedmann's past and future theory represents the scale factor of the universe ($\alpha(t)$) as a function of time. Its progression through a linear growth phase, a plateau-like, and finally a sharp increase is directly tied to the dominant energy

components of the universe (radiation, matter, and dark energy) at different epochs, more details are shown below. Stage 1, immediately after the Big Bang, the universe was dominated by radiation (photons and relativistic particles). The scale factor during this phase evolves as $\alpha(t) \propto t^{1/2}$. This slow growth is due to the high energy density of radiation, which rapidly decays as the universe expands: $\rho_{radiation} \propto \alpha(t)^{-4}$. Stage 2, as the universe cools, radiation density falls below matter density, marking the transition to a matter-dominated era, where the scale factor follows: $\alpha(t) \propto t^{2/3}$. While this growth is faster than in the radiation-dominated era, it remains slow compared to the dark energy-driven expansion in the future. This slower expansion creates the appearance of a "plateau-like" shape. Stage 3: In the dark energy-dominated era, the scale factor undergoes exponential growth: $\alpha(t) \propto e^{H_\Lambda t}$, where $H_\Lambda$ is the Hubble constant in this phase. This accelerated expansion causes the curve to steepen sharply.

In summary, the linear phase slowed expansion due to radiation domination, the plateau-like involves gradual growth during matter domination, and the sharp increase will be accelerating expansion due to dark energy domination. These transitions illustrate the interplay between radiation, matter, and dark energy in shaping the universe's history and future, which may be dominated by entropy as shown in Equation 1.2e.

## CONCLUSIONS

This pioneering research unveils a groundbreaking methodology for quantifying size-dependent nonlinearity across temporal dimensions, achieved through a concise three-entropy terms equation. This study reveals the dynamic convergence process in time:

$$\Delta\sigma = A\,(\Delta S_i) + B\,(\Delta S_i)^2 + C\,(\Delta S_i)^3 \qquad (1.2e)$$

This equation signifies a monumental achievement with sweeping implications across fundamental materials science, cosmic understanding, and cutting-edge domains such as nuclear power plants and advancements in biology. Application of Equation 1.2e in RPVs holds the promise of extending nuclear power plant lifespan from 50 to 70 years, although caution is advised against pursuing an 80-year stretch. Its simplicity and adaptability herald a transformative shift in comprehending and predicting material behaviours, charting an influential trajectory across diverse disciplines, from materials science to technological advancements. Additionally, the emergence of entropy in time space opens doors to captivating possibilities, potentially revitalizing approaches in dark matter research by capitalizing on its widespread presence throughout the universe. This revelation of fresh opportunities invites exploration into the mysterious cosmic domains that remain uncharted.

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