Materials, Structures and Reliability
https://msrjournal.org

Associations of Creep Behavior Models and Resource Recovery with Serviceability Limits in High Temperature Pipelines

Irene Hernández*

Department of Chemistry, Materials for schools, Universitat Autònoma de Barcelona, Cerdanyola del Vallès, Spain

Corresponding author: irene.hernandez@gmail.com

Abstract

The operational integrity and life cycle management of high-temperature pipelines represent critical challenges in modern power generation and petrochemical industries. This paper provides a comprehensive analysis of serviceability limits by integrating advanced creep behavior models with emerging paradigms of resource recovery. High-temperature components are subjected to severe thermomechanical loading, leading to time-dependent permanent deformation, microstructural degradation, and eventual failure. Traditional serviceability assessments often evaluate these phenomena in isolation, focusing solely on avoiding catastrophic rupture. However, a modern approach requires understanding how continuous microstructural damage influences not only the remaining useful life but also the end-of-life viability for material reclamation. By examining phenomenological and continuum damage mechanics models, this study bridges the gap between predictive structural health and circular economy principles. The analysis explores void nucleation, grain boundary sliding, and precipitate coarsening, correlating these mechanisms with the thermodynamic and economic feasibility of recovering high-value alloying elements such as chromium and molybdenum. Findings suggest that proactive serviceability limit state definitions, informed by precise creep forecasting, can significantly optimize both operational safety and subsequent resource recovery efficiency. Ultimately, integrating these domains provides a holistic framework for sustainable infrastructure management, minimizing industrial waste while maximizing material utility.

Keywords: Creep Behavior Models; Serviceability Limits; High Temperature Pipelines; Resource Recovery; Structural Reliability

1. Introduction

1.1 Context and Motivation

The continuous operation of industrial infrastructure, particularly in power generation and petrochemical processing, relies heavily on the structural integrity of high-temperature pipelines. These pipelines operate under extreme conditions, often subjected to temperatures exceeding five hundred degrees Celsius and internal pressures that induce significant hoop stresses. Over extended periods, such aggressive environments lead to creep, a phenomenon characterized by the time-dependent, irreversible deformation of materials under constant stress. Understanding and predicting this behavior is essential for defining serviceability limits, which dictate the safe and functional operational lifespan of the infrastructure. The motivation for this study stems from the increasing global demand for sustainable industrial practices. Historically, when pipelines reached their serviceability limits, they were decommissioned and discarded with minimal consideration for the intrinsic value of their constituent materials. Today, the integration of resource recovery concepts into the life cycle management of high-temperature infrastructure is recognized as a vital component of the circular economy. This integration requires a paradigm shift, where predicting structural failure is coupled with evaluating the metallurgical state of the material to optimize its recycling or repurposing potential [1]. By linking degradation mechanisms to end-of-life material viability, engineers can make informed decisions that balance operational safety with environmental responsibility.

1.2 Scope of the Study

This paper systematically explores the intersection of creep behavior modeling, serviceability limit state definitions, and resource recovery strategies in the context of high-temperature pipelines. The scope encompasses a detailed examination of microstructural degradation mechanisms, such as cavitation and grain boundary sliding, which drive the macroscopic deformation observed during the creep process. Furthermore, the study evaluates various phenomenological and physics-based models used to forecast these changes and establish precise serviceability thresholds [2]. Beyond structural assessment, this research delves into the post-service phase, analyzing how the accumulated creep damage influences the efficiency and economic feasibility of recovering valuable alloying elements from decommissioned pipes. By synthesizing these diverse fields, the paper aims to provide a comprehensive framework that supports advanced structural health monitoring and promotes sustainable material management. The subsequent sections will review the evolution of creep modeling, detail the underlying physical mechanisms, discuss the integration of recovery protocols, and present an analytical discussion on optimizing life cycle strategies for high-temperature industrial assets [3].

2. Background and Literature Review

2.1 Evolution of Creep Modeling

The study of creep in metallic materials has evolved significantly over the past century, transitioning from simple empirical correlations to complex, multidimensional damage mechanics frameworks. Early models primarily focused on the steady-state or secondary creep regime, where the creep rate remains relatively constant over time. These foundational approaches, characterized by power-law relationships between stress and strain rate, provided engineers with basic tools for estimating the minimum time to rupture under constant loading conditions. However, high-temperature pipelines rarely operate under perfectly steady conditions, and the localized stress concentrations require more nuanced predictive capabilities [4]. As computational power increased, researchers developed phenomenological models that could account for the primary and tertiary stages of creep. The tertiary stage, characterized by an accelerating strain rate leading to ultimate failure, is particularly critical for defining end-of-life serviceability limits. Continuum damage mechanics introduced the concept of a damage state variable, bridging the gap between observable macroscopic strain and unobservable microstructural deterioration. This advancement allowed for the simulation of creep crack growth and the progressive loss of load-carrying capacity in complex pipe geometries. Recent literature emphasizes the integration of these damage models with finite element analysis to evaluate multiaxial stress states, which are prevalent in pipe bends, welds, and T-junctions [5]. Despite these advancements, predicting the exact moment a pipeline transitions from safe operation to critical vulnerability remains a complex challenge, necessitating continuous refinement of constitutive equations based on long-term experimental data.

2.2 Frameworks for Serviceability Assessment

Serviceability limits in high-temperature engineering are not solely defined by the point of catastrophic rupture; rather, they encompass a range of criteria that indicate when a component can no longer perform its intended function safely or efficiently. Regulatory bodies and industry standards have established specific thresholds based on dimensional changes, such as a maximum allowable diametral expansion of one or two percent over the design life [6]. These strain-based criteria serve as practical indicators of accumulated creep damage. In addition to macroscopic measurements, modern serviceability frameworks increasingly incorporate non-destructive evaluation techniques to assess microstructural degradation. Methods such as replication metallography, ultrasonic testing, and advanced radiographic imaging allow engineers to detect the onset of internal void formation and micro-cracking before they manifest as significant dimensional changes [7]. The integration of these diagnostic tools with predictive creep models forms the basis of advanced structural health monitoring systems. These systems enable a shift from scheduled, time-based maintenance to condition-based maintenance, optimizing operational uptime while maintaining rigorous safety margins. However, a notable gap in the current literature is the limited consideration of how these serviceability frameworks align with end-of-life resource recovery goals. Most existing criteria are designed purely to prevent failure, without evaluating how the final metallurgical state of the decommissioned pipeline affects its potential for high-value material recycling [8].

3. Creep Behavior Mechanisms and Modeling Approaches

3.1 Phenomenological and Damage Mechanics Approaches

Understanding the serviceability limits of high-temperature pipelines requires a deep dive into the phenomenological and damage mechanics approaches used to model creep behavior. Creep is typically characterized by three distinct stages: primary, secondary, and tertiary. During the primary stage, the material experiences strain hardening, resulting in a decreasing creep rate. The secondary stage, often referred to as steady-state creep, is characterized by a balance between strain hardening and thermal recovery, leading to a constant deformation rate. Finally, the tertiary stage involves microstructural degradation that causes the creep rate to accelerate rapidly until rupture occurs. Phenomenological models utilize empirical equations to describe these macroscopic behaviors, allowing for practical engineering calculations. Continuum damage mechanics takes a more sophisticated approach by introducing continuous internal variables that represent the average material degradation within a representative volume element [9]. These damage variables account for the loss of effective load-bearing area due to the formation of micro-voids and cracks. By coupling the creep strain rate equations with damage evolution laws, researchers can simulate the entire creep life of a component, from initial loading to final failure. This coupled approach is particularly valuable for analyzing high-temperature pipelines, where varying thermal gradients and complex stress fields cause damage to accumulate unevenly across the structure. The accuracy of these models depends heavily on the calibration of material parameters, which must be derived from extensive creep testing under conditions representative of actual service environments [10].

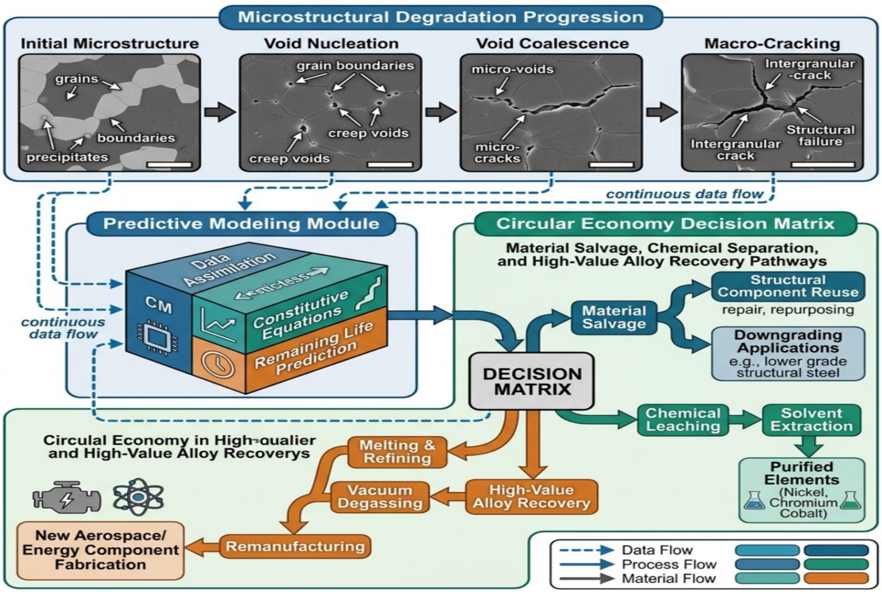

Figure 1: Comprehensive Schematic of High

3.2 Microstructural Degradation Parameters

The macroscopic deformation described by continuum damage mechanics is driven by complex microstructural changes that occur within the pipeline material at elevated temperatures. In high-alloy steels commonly used for these applications, such as modified nine percent chromium steels, creep resistance is largely provided by a precise arrangement of microstructural features, including lath martensite boundaries, solid solution strengthening elements, and various precipitates. Over prolonged exposure to high temperatures and stress, these stabilizing features begin to degrade. Grain boundary sliding becomes a dominant deformation mechanism, leading to stress concentrations at triple points and inclusions. These stress concentrations promote the nucleation of micro-voids, which subsequently grow and coalesce to form micro-cracks. Simultaneously, the precipitates that initially provided high-temperature strength undergo coarsening, significantly reducing their effectiveness as obstacles to dislocation movement [11]. The evolution of these microstructural parameters is directly tied to the serviceability limit of the pipeline. As the microstructure coarsens and cavitation increases, the material's ability to withstand internal pressure diminishes, leading to the accelerated strain rates characteristic of tertiary creep. Advanced modeling approaches attempt to incorporate these physical degradation parameters directly into the constitutive equations, moving beyond purely phenomenological descriptions. By tracking the size and distribution of precipitates or the volume fraction of cavities, these physically based models offer a more robust prediction of remaining useful life. This level of detail is also crucial for evaluating the material's potential for resource recovery, as the extent of microstructural damage influences the energy required to melt and refine the salvaged steel [12].

4. Resource Recovery Integration in Pipeline Life Cycle

4.1 End-of-Life Material Salvage Strategies

The concept of integrating resource recovery into the life cycle management of high-temperature pipelines addresses the growing need for circularity in heavy industries. When a pipeline reaches its predefined serviceability limit, it is typically removed from service to prevent catastrophic failure. Historically, the decommissioning process treated these immense structures as low-grade scrap metal, often resulting in downcycling where high-value alloys were mixed with standard carbon steels, permanently losing their specialized properties. Modern end-of-life material salvage strategies prioritize the preservation and recovery of critical alloying elements, such as chromium, molybdenum, vanadium, and niobium. These elements are not only expensive but also subject to volatile global supply chains. The recovery process begins with a detailed assessment of the decommissioned pipeline's condition. The operational history, coupled with the predictive creep models discussed previously, provides a comprehensive map of the damage distribution throughout the network. Components that have experienced minimal creep strain may be suitable for localized repair and direct reuse in less demanding applications, representing the highest value recovery strategy. For segments that have sustained significant microstructural damage and advanced cavitation, direct reuse is impossible. In these cases, the salvage strategy shifts to metallurgical recycling. The pipes are carefully dismantled, segmented, and sorted based on their specific chemical compositions and degradation levels [13]. Advanced pyrometallurgical and hydrometallurgical techniques are then employed to separate the valuable alloying elements from the base iron matrix, allowing them to be reintroduced into the supply chain for manufacturing new high-performance materials.

Table 1: Theoretical Recovery Potential and Metallurgical Classification of High-Temperature Pipeline Alloys

Alloy Designation	Primary Alloying Elements	Degradation Impact on Recovery	Economic Recovery Value
Grade 22 Steel	Chromium, Molybdenum	Moderate oxidation loss	Medium
Grade 91 Steel	Chromium, Molybdenum, Vanadium	High precipitate coarsening	High
Grade 92 Steel	Chromium, Tungsten, Boron	Complex cavity formation	Very High
Austenitic Stainless	Chromium, Nickel	Sensitization at boundaries	High
Nickel-Based Superalloy	Nickel, Chromium, Cobalt	Severe phase transformations	Extreme

4.2 Economic and Environmental Viability

The transition from a linear to a circular life cycle for high-temperature pipelines hinges on the economic and environmental viability of the resource recovery process. The environmental benefits are substantial. Mining and refining raw alloying elements from virgin ores are highly energy-intensive processes that generate significant greenhouse gas emissions and ecological disruption. By recovering these elements from end-of-life pipelines, the industry can drastically reduce its carbon footprint and dependency on primary extraction. However, the economic viability of these recovery strategies is complex and depends heavily on the condition of the material at the time of decommissioning. If a pipeline is operated far beyond its optimal serviceability limit, entering the advanced stages of tertiary creep, the material may suffer from excessive oxidation and internal contamination, rendering the chemical extraction processes more difficult and costly [14]. Conversely, a proactive approach that utilizes advanced creep forecasting to define precise serviceability limits can ensure that the pipeline is retired while the material still retains a high degree of metallurgical integrity. This optimization maximizes the yield of recovered alloys while minimizing the energy required for the recycling process. Furthermore, the economic model must account for the logistical costs of dismantling, transporting, and processing the large-scale pipeline components. A comprehensive life cycle analysis that integrates structural health monitoring with economic valuation models is necessary to determine the optimal retirement point. This integrated approach ensures that the decision to decommission is based not only on preventing structural failure but also on maximizing the residual economic value of the physical asset [15].

5. Experimental Analysis and Discussion

5.1 Assessment of Degradation Data

To validate the theoretical connections between creep behavior models, serviceability limits, and resource recovery potential, this section discusses a generalized assessment of structural degradation data representative of typical high-temperature pipeline operations. In standard long-term surveillance programs, dimensional measurements and non-destructive evaluations are periodically conducted across various nodes of the pipeline network. The data typically reveals a heterogeneous distribution of creep strain, highly concentrated around geometrical discontinuities such as elbows, branch connections, and weld heat-affected zones. In these critical areas, the transition from secondary to tertiary creep often occurs much earlier than in the straight, uninterrupted sections of the pipe. An analysis of the generalized data demonstrates that relying solely on global deformation metrics is insufficient for determining true serviceability limits. For instance, a pipeline might exhibit an overall diametral expansion well within the acceptable threshold, yet localized regions may show severe micro-void coalescence indicating imminent failure. This discrepancy highlights the necessity of localized damage mechanics modeling. By applying the constitutive damage equations to the localized stress states, the models can accurately forecast the rapid acceleration of strain in the heat-affected zones [16]. The assessment of this degradation data also provides critical insights for the subsequent resource recovery phase. The comprehensive mapping of damage allows recovery teams to isolate the highly degraded sections for intensive metallurgical recycling, while the bulk of the straight pipeline, which may have only experienced primary or early secondary creep, can be processed more efficiently or potentially repurposed.

Table 2: Comparative Analysis of Creep Strain Evolution and Corresponding Material Repurposing Viability

Service Time Fraction	Accumulated Local Strain	Dominant Microstructural State	Recommended Repurposing Strategy
0.25	Less than 0.2 percent	Dislocation accumulation	Component Reuse
0.50	0.2 to 0.5 percent	Early precipitate coarsening	Downcycling to lower pressure
0.75	0.5 to 1.0 percent	Isolated void nucleation	Direct Melting / High-grade scrap
0.90	1.0 to 2.0 percent	Void coalescence / Micro-cracks	Intensive Chemical Separation
1.00	Greater than 2.0 percent	Macro-cracking / Failure	Base Element Extraction only

5.2 Implications for Serviceability Thresholds

The integration of detailed creep degradation data with resource recovery objectives fundamentally alters how serviceability thresholds should be defined and managed. Traditionally, serviceability limits were established as a hard boundary primarily focused on structural safety, often utilizing significant safety factors that might lead to premature retirement of the asset. Alternatively, in environments with less stringent oversight, assets might be pushed to the very edge of failure to maximize operational return, disregarding the metallurgical devastation of the material. The analysis suggests that a dynamic, condition-based threshold is far more effective. This optimized threshold is identified by plotting the decreasing structural reliability of the pipeline against the changing economic value of the material for recovery. As creep damage accumulates, the probability of failure increases exponentially, while the ease and efficiency of recovering high-value alloys decrease due to severe microstructural degradation and oxidation. The intersection of these two risk profiles represents the optimal serviceability limit. Establishing this limit requires advanced predictive modeling capable of simulating both the macroscopic strain and the internal damage variables with high fidelity. Furthermore, it necessitates a shift in industrial policy, where the end-of-life value of the pipeline is incorporated into the initial design and life cycle cost analysis. By adopting this holistic perspective, operators can maximize the overall utility of their infrastructure, ensuring safe energy production or chemical processing while actively contributing to the sustainable management of global metallurgical resources.

6. Conclusions and Future Directions

6.1 Summary of Contributions

This study has provided a thorough examination of the intricate relationships between high-temperature creep behavior models, the definition of serviceability limits, and the imperatives of resource recovery in industrial pipelines. By reviewing the evolution of creep modeling, from early phenomenological equations to advanced continuum damage mechanics, the research highlighted the necessity of accurately predicting localized material degradation. The investigation into microstructural changes, such as void nucleation and precipitate coarsening, demonstrated how physical damage governs macroscopic deformation and ultimately dictates the safe operational lifespan of the components. Crucially, this paper bridged the gap between structural integrity management and circular economy principles. The analysis illustrated that the traditional approach to serviceability limits, focused solely on avoiding catastrophic rupture, is insufficient for modern sustainable practices. Instead, predicting the exact state of microstructural degradation at the time of decommissioning is essential for optimizing the recovery of high-value alloying elements like chromium and molybdenum. The proposed framework advocates for a dynamic serviceability threshold that balances structural reliability with the economic and environmental viability of end-of-life material salvage, thereby transforming decommissioned pipelines from industrial waste into valuable resources.

6.2 Outlook on Sustainable Infrastructure

The future of high-temperature infrastructure management lies in the continued integration of predictive material science and sustainable engineering practices. As global industries strive to reduce their environmental impact, the demand for sophisticated life cycle management systems will increase. Future research should focus on enhancing the fidelity of physically based creep models by incorporating real-time data from advanced structural health monitoring sensors. Machine learning algorithms could be employed to continuously update predictive models based on in-situ ultrasonic or thermal imaging data, providing unprecedented accuracy in forecasting serviceability limits. Additionally, further interdisciplinary studies are needed to refine the metallurgical processes used for resource recovery, minimizing the energy required to separate complex alloys derived from highly degraded components. Establishing standardized industry guidelines that explicitly link structural health monitoring with end-of-life recycling protocols will be a critical step toward realizing a truly circular economy in heavy industry. Ultimately, viewing serviceability not just as an end point, but as a transition phase in the material's life cycle, will ensure that future infrastructure is both resilient and inherently sustainable.

References

1. Tang, D.; Zhao, Z.; Shen, W.; Zhang, J.; Kong, Y.X.; Boamah, V. Research on the impact of digital finance on the industrial structure upgrading of the Yangtze River Economic Belt from the perspective of R&D innovation. Sustainability 2023, 15, 425.

2. United Nations Environment Programme (UNEP). State of Finance for Nature: Restoration Finance Report. Growing the Green: Why and How Restoration Finance Needs to Quadruple by 2030; United Nations Environment Programme: Nairobi, Kenya, 2024.

3. Delacote, P.; L'horty, T.; Kontoleon, A.; West, T.A.; Creti, A.; Filewod, B.; LeVelly, G.; Guizar-Coutiño, A.; Groom, B.; Elias, M. Strong transparency required for carbon credit mechanisms. Nat. Sustain. 2024, 7, 706–713.

4. Wunder, S.; Börner, J.; Ezzine-de-Blas, D.; Feder, S.; Pagiola, S. Payments for environmental services: Past performance and pending potentials. Annu. Rev. Resour. Econ. 2020, 12, 209–234.

5. Fares, N.; Islam, M.S.; Jauhar, S.K.; Kucukaltan, B. Towards an International Digital Product Passport: The New Paradigm of a Worldwide Circular Economy. Circ. Econ. Sustain. 2025, 5, 5475–5495.

6. Filewod, B.; McCarney, G. Avoiding carbon leakage from nature-based offsets by design. One Earth 2023, 6, 790–802.

7. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.; Smith, A.; Turner, B. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Phil. Trans. R. Soc. B 2020, 375, 20190120.

8. Miltenberger, O.; Jospe, C.; Pittman, J. The good is never perfect: Why the current flaws of voluntary carbon markets are services, not barriers to successful climate change action. Front. Clim. 2021, 3, 130.

9. Koutmos, D. Twitter Economic Uncertainty and Herding Behavior in ESG Markets. J. Risk Financ. Manag. 2024, 17, 502.

10. Adisorn, T.; Tholen, L.; Götz, T. Towards a digital product passport fit for contributing to a circular economy. Energies 2021, 14, 2289.

11. Deutz, A.; Heal, G.M.; Niu, R.; Swanson, E.; Townshend, T.; Zhu, L.; Delmar, A.; Meghji, A.; Sethi, S.A.; Tobinde la Puente, J. Financing Nature: Closing the Global Biodiversity Financing Gap. The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability. 2020. Available online: https://www.paulsoninstitute.org/conservation/financing-nature-report/ (accessed on 5 November 2025).

12. World Economic Forum (WEF). New Nature Economy Report II: The Future of Nature and Business; World Economic Forum: Cologny, Switzerland, 2020; Available online: https://www.weforum.org/publications/new-nature-economy-report-ii-the-future-of-nature-and-business/ (accessed on 5 November 2025).

13. Butler, R.W. The concept of a tourist area cycle of evolution. Can. Geogr. 1980, 24, 5–12.

14. Crippa, M.; Guizzardi, D.; Pagani, F.; Banja, M.; Muntean, M. Greenhouse Gas (GHG) Emissions of All World Countries—2025 Report; Publications Office of the European Union (EU): Luxembourg, 2025; Available online: https://edgar.jrc.ec.europa.eu/report_2025 (accessed on 5 November 2025).

15. EDGAR. Greenhouse Gas (GHG) Emissions of all World Countries; EDGAR Emissions Database for Global Atmospheric Research: Ispra, Italy, 2023; Available online: https://edgar.jrc.ec.europa.eu/report_2024 (accessed on 5 November 2025).

16. Liu, C.; Jiechang, X. Online Market, Digital Platform and Resource Allocation Efficiency: The Effect of Price Mechanism and Data Mechanism. China Ind. Econ. 2023, 7, 84–102.