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Original Article

A Proposed Regulatory Framework for Ageing Management of Nuclear Research Reactors: Evidence from the Brazilian IPR-R1 TRIGA® Case

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Abstract: Nuclear Research Reactors (NRRs) are essential infrastructures for radioisotope production, materials research, education, training and technological development related to low-carbon energy systems. A large share of the global NRR fleet has operated for several decades, which increases the regulatory relevance of physical degradation, technological obsolescence and preservation of organizational knowledge. This paper proposes a graded regulatory framework for ageing management of Brazilian research reactors, using the IPR-R1 TRIGA® reactor as an applied regulatory case. The method combines documentary and normative analysis, comparative assessment of international guidance and a regulatory-technical case study. The evidence base included IAEA safety standards and reports, U.S. NRC non-power reactor guidance, Brazilian licensing instruments, the IPR-R1 ageing management documentation and the institutional transition from Brazilian Nuclear Energy Commission (CNEN) to Brazilian Nuclear Safety Authority (ANSN). The results show that ageing management for research reactors should not be treated as a direct equivalent of long-term operation or license renewal for power reactors. Instead, it should be structured as a continuous, risk-informed and auditable regulatory process. The proposed framework is organized around five elements: mandatory ageing management programmes; screening and classification of structures, systems and components important to safety; TLAA-equivalent or residual-life assessments when original time-limited design data are unavailable; periodic safety review as an integrated regulatory anchor; and clear allocation of responsibilities between the operator and the regulatory body. The Brazilian IPR-R1 case demonstrates the feasibility of using existing operational, maintenance and licensing evidence to support continued safe operation, provided that the evidence is consolidated into a traceable regulatory model. The study concludes that a specific regulation or preparatory technical note for research reactors would improve regulatory predictability, institutional coherence and alignment with international best practices.

Keywords: ageing management; research reactors; nuclear regulation; IPR-R1 TRIGA®; structures, systems and components; Time-Limited Ageing Analyses; Periodic Safety Review; energy transition.

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Uma Proposta de Estrutura Regulatória para a Gestão do Envelhecimento de Reatores Nucleares de Pesquisa: Evidências do Caso Brasileiro do IPR-R1 TRIGA®

Resumo: Reatores Nucleares de Pesquisa (RNPs) são infraestruturas essenciais para a produção de radioisótopos, pesquisa de materiais, educação, treinamento e desenvolvimento tecnológico relacionado a sistemas de energia de baixo carbono. Uma grande parcela da frota global de RNPs opera há várias décadas, o que aumenta a relevância regulatória da degradação física, da obsolescência tecnológica e da preservação do conhecimento organizacional. Este artigo propõe uma estrutura regulatória graduada para a gestão do envelhecimento de reatores de pesquisa brasileiros, utilizando o reator TRIGA® IPR-R1 como caso regulatório aplicado. O método combina análise documental e normativa, avaliação comparativa de diretrizes internacionais e um estudo de caso técnico-regulatório. A base de evidências incluiu normas e relatórios de segurança da AIEA, diretrizes da NRC dos EUA para reatores não destinados à geração de potência, instrumentos de licenciamento brasileiros, a documentação de gestão do envelhecimento do IPR-R1 e a transição institucional da Comissão Nacional de Energia Nuclear (CNEN) para a Autoridade nacional de Segurança Nuclear (ANSN). Os resultados mostram que a gestão do envelhecimento para reatores de pesquisa não deve ser tratada como um equivalente direto da operação de longo prazo ou da renovação de licença para reatores de potência. Em vez disso, deve ser estruturada como um processo regulatório contínuo, auditável e fundamentado em riscos. A estrutura proposta organiza-se em torno de cinco elementos: programas obrigatórios de gestão do envelhecimento; triagem e classificação de estruturas, sistemas e componentes importantes para a segurança; avaliações equivalentes a TLAA (Análises de Envelhecimento com Limite de Tempo) ou de vida útil residual quando os dados originais de projeto com limite de tempo não estiverem disponíveis; revisão periódica de segurança como um pilar regulatório integrado; e atribuição clara de responsabilidades entre o operador e o órgão regulador. O caso brasileiro do IPR-R1 demonstra a viabilidade de utilizar evidências operacionais, de manutenção e de licenciamento existentes para embasar a continuidade da operação segura, desde que tais evidências sejam consolidadas em um modelo regulatório rastreável. O estudo conclui que uma regulamentação específica ou uma nota técnica preparatória para reatores de pesquisa melhoraria a previsibilidade regulatória, a coerência institucional e o alinhamento com as melhores práticas internacionais.

Palavras-chave: gerenciamento do envelhecimento; reatores de pesquisa; regulação nuclear; IPR-R1 TRIGA®; estruturas, sistemas e componentes; TLAA; revisão periódica de segurança; transição energética.

1. INTRODUCTION

The global energy transition is increasingly shaped by the combined objectives of decarbonization, energy security and system resilience. Variable renewable energy sources have expanded rapidly, but their variability requires complementary infrastructures capable of supporting technological continuity, system adequacy and institutional resilience. Nuclear Research Reactors (NRRs) contribute to this ecosystem in a different way from power reactors: they do not primarily supply electricity, but they support radioisotope production, neutron activation analysis, materials testing, education and training, fuel and materials qualification, and research associated with advanced nuclear technologies and hydrogen production [1-4].

The strategic role of NRRs depends on their continued safe operation. The global fleet is heterogeneous and includes many facilities that were designed and licensed under technological and regulatory assumptions different from contemporary safety expectations. Ageing therefore becomes a regulatory concern that includes physical degradation, obsolescence of Instrumentation and Control (I&C) systems, changes in safety standards and preservation of institutional knowledge [1,5,6].

The Brazilian context illustrates these challenges. The IPR-R1 TRIGA® research reactor, located at the Nuclear Technology Development Centre (CDTN), reached first criticality in 1960 and has supported education, research and nuclear applications for more than six decades. Its case is relevant not because it represents all Brazilian reactors, but because it provides a concrete regulatory example of how ageing management may be documented, reviewed and connected to licensing conditions [7-9].

This paper addresses the following question: how can ageing management for nuclear research reactors be structured as an enforceable regulatory instrument in Brazil, while avoiding the inappropriate transposition of Long-Term Operation (LTO) concepts developed for nuclear power plants? The objective is to propose a graded regulatory framework that combines international best practices with the Brazilian regulatory and institutional context. The contribution is not a repetition of previous technical descriptions of the IPR-R1 ageing management plan. The novelty lies in transforming the case evidence into a regulatory model, including definitions, scope, regulatory functions and decision logic applicable to research reactors.

1.1. Regulatory Background

Ageing is the cumulative time-dependent or use-dependent change that can affect SSC performance. Ageing management is the organized set of engineering, operational and administrative actions used to identify, monitor, mitigate and control ageing effects. Continued operation is a regulatory decision that a reactor may continue to operate under defined conditions because its safety functions remain preserved. LTO, in the power-reactor sense, is a formal process for operation beyond a defined license or design period. These concepts overlap but are not interchangeable.

For research reactors, this distinction is central. Many facilities operate under licensing paradigms that do not establish the same fixed design lifetime or license renewal structure used for power reactors. A research reactor may operate for 60 years or more without that fact alone constituting LTO in the power-reactor sense. The regulatory question is not whether the reactor is old, but whether the operator can demonstrate that SSCs important to safety continue to perform their required functions and that ageing effects are controlled within acceptable limits.

An SSC-based approach is the foundation of such a demonstration. It links ageing phenomena to safety functions and regulatory priorities. In research reactors, relevant SSCs may include the core support structures, fuel assemblies, control rod drive mechanisms, primary cooling systems, pool or tank structures, I&C systems, confinement or shielding structures, electrical systems and supporting utilities. Ageing mechanisms may include corrosion, fatigue, irradiation effects, thermal degradation, wear, erosion, elastomer degradation, obsolescence of components and documentation, and loss of supplier support [1,5,8].

Periodic Safety Review (PSR) provides the integrated regulatory mechanism through which the effectiveness of ageing management can be reassessed. For research reactors, PSR should not be treated merely as a power-reactor import. It should be applied in a graded manner, with scope and depth proportional to reactor power, inventory, mission, operating history and risk significance. The PSR should consolidate ageing management performance, operational experience, modifications, updated safety standards, human and organizational factors, knowledge management and external hazards [6].

1.2. Brazilian case: IPR-R1 TRIGA®

The IPR-R1 TRIGA® reactor is a Triga Mark I research reactor installed at CDTN. It reached first criticality in 1960 and was initially operated at 30 kW thermal power. Subsequent core and instrumentation changes allowed higher technical capability, but current operation has been limited according to safety and regulatory considerations. This history makes the reactor a valuable case for examining ageing management as a continuous regulatory process rather than as a single life-extension event [8,9].

The ageing management experience of IPR-R1 includes technical and organizational aspects. Physical ageing is associated with SSCs exposed to irradiation, water chemistry, thermal cycles, mechanical loads and long service periods. Technological ageing is associated especially with I&C systems, supplier support and documentation. The Brazilian documentation identifies corrosion as an important degradation concern and highlights inspection, maintenance, water quality control and modernization as relevant control strategies [8,9].

The case also shows how regulatory conditions can transform ageing management into an auditable obligation. Resolution CNEN nº 226/2018 granted the Permanent Operation Authorization for the IPR-R1 reactor and required actions connected to safety reassessment, updating of safety documentation and implementation of ageing management instruments [7]. The ageing management plan prepared by CDTN provides a structured basis for identifying SSCs, mechanisms, monitoring activities, maintenance actions and improvement processes [8].

From a regulatory perspective, the IPR-R1 case should not be presented as the full Brazilian framework. It is an applied case that demonstrates feasibility, limitations and lessons. The principal lesson is that existing evidence may support continued safe operation only if it is organized in a traceable structure that connects SSC screening, ageing mechanisms, monitoring data, acceptance criteria, corrective actions, documentation updates and periodic regulatory review.

2. MATERIALS AND METHODS

This study is an applied qualitative regulatory analysis. It does not present new experimental measurements of material degradation. Instead, it develops a structured regulatory proposal based on documentary evidence, comparative normative analysis and interpretation of an applied Brazilian case. This methodological choice is appropriate because the research problem is not the quantification of a single degradation mechanism, but the design of regulatory requirements capable of ensuring that such mechanisms are identified, monitored and controlled.

The analysis used four groups of evidence. The first group comprised international safety standards and guidance, especially IAEA SSG-10 (Rev. 1), SSR-3, SSG-24 and Safety Reports Series nº 99, which address research reactor safety, ageing management, modifications and periodic safety review [1,5,6,10]. The second group comprised U.S. NRC non-power reactor guidance, especially NUREG-1537, because it provides a licensing review structure for non-power reactors without importing the complete power-reactor license renewal regime [11]. The third group comprised Brazilian regulatory and institutional instruments, including CNEN NE 1.04, Resolution CNEN nº 226/2018, the transition from CNEN to ANSN and the need to consolidate regulatory expectations for ageing management [7,12,13]. The fourth group comprised the IPR-R1 TRIGA® case documentation, including the ageing management plan, safety analysis records, operating experience and regulatory-technical analyses available to the authors [8,9].

The review followed three analytical steps. Step 1 identified regulatory functions consistently required or recommended in international practice: Screening of Systems, and Components (SSCs) important to safety, ageing mechanism identification, monitoring, inspection, acceptance criteria, corrective actions, obsolescence management, operating experience feedback and periodic reassessment. Step 2 compared these functions with the Brazilian regulatory framework and the IPR-R1 documentation. Step 3 transformed the identified gaps and convergences into a graded regulatory framework with proposed responsibilities for the operator and the regulatory authority.

For Time-Limited Ageing Analyses (TLAA), the method adopted a graded interpretation. In power reactors, TLAA are usually connected to original design analyses with explicit time assumptions. Many research reactors, especially older low-power facilities, may not have complete original time-limited design data. Therefore, this paper does not recommend a literal transposition of the power-reactor TLAA model. Instead, it proposes TLAA-equivalent or residual-life assessments based on available design information, inspection results, operating history, water chemistry records, maintenance data, modifications and conservative engineering judgement. This interpretation is consistent with the current international discussion on developing TLAA methodologies for research reactors [14].

Table 1: Methodological design and evidence base

Step	Evidence base	Analytical output
Documentary and normative review	IAEA, U.S. NRC and Brazilian instruments	Identification of regulatory functions and terminology
Comparative regulatory assessment	International guidance versus Brazilian framework	Identification of gaps, convergences and adaptation needs
Regulatory-technical case study	IPR-R1 TRIGA® licensing and ageing management documentation	Applied evidence for framework construction
Synthesis and proposal	Results from the previous steps	Graded regulatory framework for research reactors

Source: by authors

3. RESULTS AND DISCUSSIONS

The comparative analysis identified five main regulatory gaps and corresponding modernization actions. First, the Brazilian framework lacks a specific and systematized instrument for ageing management of research reactors. Second, terminology has been used inconsistently, with ageing management sometimes being approached as if it were equivalent to life extension. Third, TLAA concepts require adaptation because older research reactors may lack complete original time-limited design analyses. Fourth, PSR should be explicitly connected to ageing management and interim reviews. Fifth, the evidentiary basis for regulatory decisions must be made more traceable and auditable.

The proposed framework responds to these gaps by treating ageing management as a mandatory regulatory function applicable throughout the operational life of a research reactor. It is based on five operational requirements: an approved ageing management programme; documented SSC screening and classification; condition-based TLAA-equivalent assessments where appropriate; periodic safety review as an integrated decision anchor; and allocation of responsibilities between the operator and the regulatory authority.

The role of TLAA in this framework is deliberately limited and adapted. When original time-limited design assumptions exist, they should be reviewed and updated. When they do not exist, the operator should perform residual-life or condition-based assessments using available evidence. Such assessments should not be presented as a reconstruction of unavailable design assumptions unless the technical basis is defensible. They should instead identify degradation mechanisms, current condition, trends, uncertainties, acceptance criteria and compensatory measures. This approach avoids the technical weakness of imposing a power-reactor TLAA model on research reactors without sufficient data.

PSR is positioned as the regulatory anchor for continued operation. A ten-year review may be appropriate as a general reference, but the framework also requires interim reviews triggered by relevant conditions, such as significant modifications, unexpected degradation, safety-significant events, changes in mission, prolonged shutdown, major I&C modernization or updates in safety standards. This responds to the concern that PSR applied without intermediate feedback may be insufficient for long-operating research reactors.

The framework also incorporates proportionality. A low-power training and research reactor should not be subject to the same depth of analysis as a high-flux reactor or a power reactor. However, proportionality does not mean absence of control. It means that regulatory requirements should be graded according to safety significance, reactor power, inventory, utilization, degradation susceptibility and quality of the available evidence.

Finally, the relationship with energy transition is indirect but relevant. Research reactors support nuclear innovation, qualification of materials and fuels, radioisotope supply and human capital. Their safe continued operation strengthens technological sovereignty and supports future low-carbon applications. The energy-transition argument is therefore retained in the revised paper, but it is no longer used as the main proof of originality. The main contribution is the regulatory framework itself.

Table 2: Main regulatory gaps and proposed modernization actions

Regulatory dimension	Observed gap	Proposed action
Specific regulation	No systematized ageing management instrument for research reactors	Issue a specific technical note, guide or regulation for research reactors
Terminology	Ambiguity between ageing management, life extension and LTO	Define concepts operationally and avoid direct transposition from power reactors
TLAA	Original time-limited design data may be absent or incomplete	Use TLAA-equivalent or residual-life assessments based on inspections, history and conservative judgement
PSR	Need for integration between periodic reassessment and ageing management	Adopt graded PSR with interim review triggers
Evidence	Operational evidence may be dispersed across documents	Require traceable records, acceptance criteria and corrective action history

Source: by authors

3.1. Proposed regulatory framework

The proposed framework is designed as a preparatory model that could support a technical note, regulatory guide or future binding regulation by ANSN. It is not presented as a draft resolution to be adopted without institutional review. Its purpose is to define the regulatory architecture needed for a specific ageing management instrument for research reactors. The framework should include the following minimum elements: (i) object and scope, limited to research reactors; (ii) definitions of ageing, ageing management, physical ageing, non-physical ageing, SSCs important to safety, continued operation and TLAA-equivalent assessment; (iii) principles of nuclear safety, primary responsibility of the operator, proportionality, risk-informed decision-making, traceability and continuous improvement; (iv) mandatory ageing management programme; (v) minimum programme content; (vi) periodic safety review and interim review requirements; (vii) regulatory review, inspection and enforcement provisions; and (viii) transitional provisions for reactors already in operation. The operator should be responsible for implementing the ageing management programme, maintaining records, demonstrating the effectiveness of monitoring and corrective actions, updating safety documentation and submitting evidence to the regulator. The regulatory body should define requirements, review the programme, verify implementation through inspections and audits, impose conditions where necessary and ensure that ageing management remains aligned with updated safety standards.

This structure strengthens regulatory predictability. It avoids both under-regulations, where ageing management is dispersed across maintenance practices, and over-transposition, where research reactors are treated as if they were power reactors subject to license renewal requirements that do not fit their design, mission or risk profile.

Figure 1: Proposed graded regulatory framework for ageing management of research reactors

Regulatory basis IAEA SSG-19 Rev.1; SSR-3; NRC Nureg-1537; CNEN NE 1.04
Mandatory AMP Ageing management programme with acceptance criteria, records and corrective action
Screening and classification SSCs important to safety; ageing susceptibility; risk significance and operating conditions
TLAA-equivalent/ RLA Residual-life or condition-based assessments when original time-limited data are unavailable
Evidence base Operation history; inspections; maintenance; water chemistry; modifications; operating experience
PSR/ continued operation decision Integrated reassessment, interim reviews and regulatory conditions

Source: adapted from based on IAEA SSG-10 Rev. 1; SSR-3, U.S. NRC Nureg-1537 and Brazilian regulatory evidence.

4. CONCLUSIONS

This paper proposes a graded regulatory framework for ageing management of nuclear research reactors, using the Brazilian IPR-R1 TRIGA® reactor as an applied regulatory case. The analysis shows that ageing management should be understood as a continuous and auditable regulatory function, not as a direct equivalent of life extension or LTO in the power-reactor sense.

The main result is a framework based on mandatory ageing management programmes, SSC screening and classification, TLAA-equivalent or residual-life assessments when original time-limited design data are absent, periodic safety review as a regulatory anchor, interim review triggers and clear allocation of responsibilities between the operator and the regulatory authority.

The IPR-R1 case demonstrates that existing operational and licensing evidence can support continued safe operation when organized in a traceable structure connecting degradation mechanisms, monitoring, maintenance, safety documentation, corrective actions and regulatory review. This case also demonstrates the need for a specific national regulatory instrument for research reactors, especially in the context of the institutional transition from CNEN to ANSN.

The study contributes to regulatory literature by offering a model that is specific to research reactors, compatible with international safety standards and applicable to countries with limited resources and ageing research reactor fleets. Future work should validate the framework through broader comparison with other Brazilian and international research reactors and through regulatory consultation with operators and the competent authority.

Ultimately, the long-term value of nuclear research reactors depends not on their age, but on the quality and robustness of the regulatory frameworks that govern their operation over time. By elevating aging management to the level of policy design, regulators and decision-makers can ensure that these facilities continue to serve as reliable pillars of safety, innovation, and resilience in a decarbonized energy system.

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CONTRIBUTORSHIP

Conceptualization: AVE1, MAZ2, PDAP3

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Interview transcripts and qualitative data are not publicly available due to confidentiality commitments made to research participants. Aggregated data supporting the findings are available from the corresponding author upon reasonable request and subject to participant privacy protections.

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