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Magic-RR Project overview: Objectives, methodology and expected results

M. Kolluri[1], F. Naziris[1], B. Tanguy[2], P. Francois[2], F. Gillemot[3], I. Szenthe[3], J. A. W. van Dommelen[4], Y. Gonzalez-Garcia[5], B. Radiguet[6], P. Bagot[7], A. London[8], H. Namburi[9], J. Mostert[10]

[1]NRG - The Netherlands, [2]CEA - France, [3]HUN-REN-CER - Hungary, [4] Eindhoven University of Technology - The Netherlands, [5]TU Delft - The Netherlands, [6]University of Rouen - France, [7]University of Oxford - UK, [8]UKAEA – UK, [9]CNL - Canada, [10]NECSA – South Africa.

[*]*Corresponding author: M. Kolluri Tel: +31 615695319, e-mail: kolluri@nrg.eu*

Abstract

Most research reactors (RRs) in Europe are over 60 years old, and there are only limited efforts underway (e.g., PALLAS and JHR projects) to partially replace this aging infrastructure. Continued safe operation (CSO) of these reactors is crucial to sustaining the EU's leadership in nuclear materials development and qualification for advanced reactor designs and ensuring a steady supply of medical isotopes. Extending the licenses for these reactors to ensure CSO requires comprehensive aging management reviews (AMRs) and time-limited aging analyses (TLAAs) of key structures and components. However, current challenges include a limited understanding of irradiation-induced degradation and corrosion mechanisms, a shortage of data on RR structural materials under high-fluence conditions necessary for CSO, the lack of predictive, physics-based models for irradiation damage in aluminum alloys, and insufficient surveillance specimens for some reactors. Additionally, there are no dedicated design codes for reactor vessels and core structures made of aluminum, and there is no standardized approach in Europe for aging management of operating RRs.

To address these issues, a new project, Research on Materials Ageing and Structural Integrity of Research Reactors (Magic-RR), was launched on 1st of November 2024, funded by the EURATOM research and training program 2023 with contributions from several international partners including RR operators, new RR developers and technical universities. Magic-RR will leverage (1) available archive materials and data from the existing RRs, e.g. from surveillance programs and shut down reactors, (2) operational experience of RR operators and (3) advanced characterization and modelling techniques at universities and nuclear research centers, to achieve the following objectives to support the CSO of European RRs:

- Enhancing understanding of irradiation-induced damage in RR structural materials, particularly aluminum alloys, under high-fluence conditions
- Develop advanced multi-scale modeling techniques to predict irradiation effects on mechanical properties
- Investigating corrosion mechanisms and developing strategies for their prevention and mitigation
- Assessing and validating sub-size testing methods for surveillance programs
- Sharing operational knowledge on ageing management and structural integrity assessment of critical RR components and establishing guidelines for best practices

This paper provides comprehensive description of the objectives, methodology, expected results and impact of the Magic-RR project.

Keywords: Research reactors, continued safe operation, irradiation damage of aluminum alloys, transmutation damage, materials ageing, structural integrity

Nomenclature

Acronym	Description
AMR	Ageing Management Review
APT	Atom Probe Tomography
CSO	Continued Safe Operation
CT	Compact Tension
EDM	Electrical Discharge Machining
EDX/EDAX	Energy Dispersive X-Ray Spectroscopy
EU	European Union
EUG	End-User Group
FEM	Finite Element Modelling
FIB	Focused Ion Beam
FT	Fracture Toughness
HFR	High Flux Reactor in Petten
HLOs	High Level Objectives
IAEA	International Atomic Energy Agency
LEU	Low Enriched Uranium
OM	Optical Microscopy
PIE	Post-Irradiation Examination
RRs	Research Reactors
RVE	Representative Volume Element
SANS	Small angle neutron scattering
SCC	Safety Critical Components
SEM	Scanning Electron Microscope
SKPFM	Scanning Kelvin Probe Force Microscopy
SOs	Specific objectives
SURP	HFR Vessel Surveillance Programme
TEM	Transmission Electron Microscope
TFR	Thermal-to-Fast Fluence Ratio
TLAA	Time Limited Ageing Analysis
TSOs	Technical and scientific support organizations
XPS	X-Ray Photoelectron Spectroscopy

1 Introduction

Research reactors (RRs) play a crucial role in the development of nuclear science and technology. The neutrons produced in the RRs, are a versatile tool for nuclear research, material characterization and testing, neutron scattering and radiography and essential for the development and production of radioisotopes that are used for the diagnosis and treatment of diseases. In addition, RRs are important tools of advance education and training on nuclear technology for energy and other applications [1]. There is a wide array of designs for research reactors and an even wider array of applications that offer socio-economic benefits to help countries worldwide achieve their sustainable development objectives [2].

According to the IAEA research reactor database [3], a total of 224 RRs are currently in operation in the entire world, while only 9 new RRs are currently under construction. Majority of the operating RRs have exceeded the 40 years of operation. Specifically in Europe, operating RRs are very old (>60 years operation) approaching the end of their design life. Only few initiatives are taken (PALLAS [4] and Jules Horowitz Reactor [5]) to partially replace this capacity. Continued safe operation of these RRs is mandatory (at least until the new reactors come to operation) to maintain the EU excellence in development and qualification of nuclear materials for advanced reactor concepts and to maintain the supply of medical isotopes. License extensions for continued safe operation (CSO) require ageing management review (AMR) and time limited ageing analysis (TLAA) to demonstrate structural integrity of safety-critical structures and components such as the reactor vessel.

However, there is limited understanding of ageing mechanisms and lack of data on RR materials at relevant operating conditions for long term operation of RRs. In addition, there is a shortage of surveillance specimens for extending the operational life for some RRs. Lastly, sharing of knowledge and operational experience is crucial in this relatively small RR community.

A more detailed description of ageing mechanisms and open issues in RR materials, the high level, and specific objectives, applied methodology, expected results and impact of Magic-RR, extracted from the original project proposal [6], are provided in the following sections.

2 Open issues

Low-temperature water-cooled-and-moderated RRs, typically employ 5xxx or 6xxx series aluminum (Al) alloys as a material for the reactor vessel and in-core components, due to their fair mechanical properties, corrosion resistance, irradiation swelling resistance properties and low thermal neutron capture cross section. Some of these components are practically non-replaceable, yet experience hardening and toughness reduction due to radiation exposure. Throughout the lifetime, these materials are exposed to large neutron fluence values (in some cases even up to ~10^{27}n/m^2). The damage caused by neutron irradiation is the major degradation mechanism leading to irradiation hardening and embrittlement of Al alloys used in RRs. Both thermal and fast neutrons cause damage in Al alloys. Displacement damage by fast neutrons and transmutation damage by both thermal and fast neutrons are the two major damage mechanisms in irradiated Al alloys [7, 8, 9]. Fast neutrons produce gaseous products like He and H through (n, α) and (n, p) transmutation reactions. Gaseous transmutation products can have a substantial influence on the irradiation damage structure by promoting cavity formation and swelling. Alloys that promote trapping and recombination of point defects reduce vacancy supersaturation and hence exhibit increased resistance to cavity formation and swelling [7]: 5052-O and 6061 alloys have an excellent resistance to cavity formation and swelling, with respect to pure Al and grade 1100 alloys. On the other hand, thermal neutrons cause transmutation of Al into Si through the following sequential reactions: $^{27}Al(n,\gamma)^{28}Al$, $^{28}Al \rightarrow {}^{28}Si + \beta$. These reactions will cause the increase in Si-content in the Al alloys as function of neutron fluence. Kapusta et al. [10] confirmed that the transformation Si-content is a major irradiation damage mechanism in Al alloys. The solubility of Si in the Al matrix below 373 K is negligible. Hence, the transmutation-produced Si will either precipitate in elemental form as in pure Al, grade 1100 and 6061 alloys or forms Mg_2Si precipitates as in 5xxx series alloys until all the Mg in solid solution is consumed. The structure, size, and distribution of these precipitates (Si and Mg_2Si) in the microstructure will determine the resulting mechanical properties of irradiated alloys. The relative contribution of these different damage mechanisms and the resulting impact on the mechanical properties depend on the alloy composition and microstructure, thermal-to-fast fluence ratio (TFR), irradiation temperature, and other irradiation conditions.

Large amount literature was published on the irradiation behavior of various aluminum alloys up to thermal fluence values of ~$30x10^{26}$ n/m^2 [11, 12, 13, 14, 10]. However, there is a limited understanding of the materials degradation mechanisms and insufficient materials data, specifically fracture toughness (FT) data at high fluence conditions (>~$30x10^{26}$ n/m^2). In literature, indications of an abrupt transition towards brittle behavior at higher fluences were found [11]. For the development of accurate irradiation damage prediction models, a deeper understanding of irradiation damage mechanisms and more mechanical testing data (tensile properties, fracture toughness etc.) in the high fluence regime are necessary. With the studies on both highly irradiated 5xxx and 6xxx alloys planned within Magic-RR, these knowledge gaps are aimed to be filled.

In addition, in the reactor pool environment, the Al alloys are subjected to corrosion and the growth of aluminum hydroxide can degrade the heat exchange between the core components and the coolant due to lower thermal conductivity [15]. The oxidation of the Al alloys, used as fuel cladding, becomes critical in the case of the use of low enriched uranium (LEU) fuels since the formation of oxide elevates the fuel temperature and decreases the fuel performance [16]. Understanding the corrosion behavior of Al alloys in radiation field, as well as studying mitigation strategies to increase their corrosion resistance is thus highly important for safe operation of RRs. Different mitigation strategies, such as anodizing or hydrothermal treatments, can be used. Studying the impact of different parameters (pH, water chemistry) on the corrosion of Al alloys and the influence of different mitigation strategies on corrosion resistance is necessary.

Another challenge for the CSO of RRs, is the lack of surveillance specimens. A proposed strategy to solve this issue, is testing of sub-sized specimens. Evaluation of the applicability of smaller specimens for irradiated Al alloys is required for regulatory acceptance of smaller specimens for surveillance testing.

Finally, comprehensive ageing management and periodic safety reviews are critical steps for CSO of RRs. The operating conditions and hence failure scenarios widely differ from power reactors. It is a fact, that only a few RRs operate at high pressures and temperatures so that the power reactors safety code can be applied for them. Most of the research reactors operated at low temperature, are not pressurized, and have cores built from aluminum alloys. No pressurized thermals shock can occur, and the risk of brittle fracture is extremely low for these reactors. On the other hand, the loss of coolant or the failure of in-core or near core structures can cause serious accidents, including the failure of the fuel elements and radiation release, consequently the ageing behavior of the Safety Critical Components (SCC) should be actively managed and monitored, and the necessary mitigation actions should be performed. However, this is a challenge because in most countries there are no separate codes for reactor vessel and core structures made of aluminum and there is no European conformity regarding the ageing management of operating RRs.

3 Objectives and planned activities

To address the aforementioned open issues in RRs, the following 3 high level objectives (HLOs) and 9 specific objectives (SOs) are defined in Magic-RR. These are listed below, together with the activities planned to achieve the mentioned objectives and the expected results.

HLO1: Improve the current understanding of the irradiation-induced degradation behavior and corrosion mechanisms in aluminum alloys in RRs. Filling the existing knowledge and data gaps on this topic will contribute to the safe continued operation of RRs in Europe and will also provide valuable input for the design of future RRs.

To achieve HLO1, the following SO1-SO4 are defined, which focus on a deeper understanding of the ageing mechanisms of Al alloys in operation conditions of RRs.

SO1: Quantitative characterization of hardening and toughness reduction of Al alloys, as a function of thermal neutron fluence and alloy composition

It is known that neutron irradiation will affect the mechanical properties of the aluminum alloys. Due to the limited understanding of the materials behavior in the high fluence regime and the lack of publication of high-fluence mechanical properties data (tensile and FT), an extensive Post-Irradiation Examination (PIE) mechanical testing campaign on a wide range of RR Al alloys, irradiated to different neutron fluences, is planned within the Magic-RR project.

Activities planned: Tensile testing, notch tensile testing, hardness testing, nanoindentation and FT testing (CT and 3-point bending specimen geometries) will be applied.

Expected outcome: Wide range of data related to irradiation hardening and toughness reduction of Al alloys, as a function of alloy composition and thermal neutron fluence.

SO2: Investigation of irradiation damage on the microstructures of the different RR materials and correlation to the changes in mechanical properties

In order to understand the mechanical behavior of the RR Al alloys measured in SO1, a complete characterization of their microstructures and radiation induced defects is needed.

Activities planned: Microstructural characterization using Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). Characterization of radiation induced defects by means of Atom Probe Tomography (APT), Small Angle Neutron Scattering (SANS) and TEM.

Expected outcome: Understanding the effect of initial microstructure and chemical composition on the irradiation behavior, determination of Si transmutation effects in the different Al alloys, quantification of voids and any associated swelling in the studied materials. The observed changes in microstructure will be correlated to the mechanical properties for different fluence values.

SO3: Development of predictive models for irradiation damage in RR materials

Currently, there is a lack of accurate predictive models for the irradiation damage behavior of RR materials, at the high fluence regimes relevant for CSO. Hence, a framework for modelling the microstructural evolution under different neutron fluences, and the consequential irradiation hardening and embrittlement of an RR alloy will be developed.

Activities planned: Use of multi-scale approach to correlate physical processes, which occur at the scale of the crystalline lattice and its defects, to the mechanical failure at the scale of macroscopic application. The combined use of cluster dynamics, crystal plasticity and probabilistic brittle failure models will be employed and the material to be considered is the 5154-O alloy. Data obtained in SO1 and SO2 will be used as input.

Expected outcome: A fundamental insight in the processes that govern the failure behavior and its evolution under irradiation fluences. This will enable the development of improved radiation-resistant materials and will be instrumental for the interpretation of standard and non-standard test data.

SO4: Improve the current understanding on the corrosion behavior of Al alloys during operation conditions and evaluate the effectiveness of prevention and mitigation strategies

Activities planned: Preparation of literature review about the corrosion behavior of Al alloys used in RRs, investigation of the effect of different hydrothermal treatments and anodizing on the corrosion resistance of Al alloys, during the exposure to RR operation environment and during neutron irradiation and characterization of corrosion products using SEM, EDX and SPX analyses. Finally, Scanning Kelvin Probe Force Microscopy (SKPFM) will be used to obtain surface potential maps at the sub-micrometer scale and elucidate the reactivity differences between microstructural features, in particular intermetallic phases, and segregates, aiming at identifying corrosion initiation sites.

Expected outcome: Understanding the influence of time and temperature on the effectiveness of hydrothermal treatments and anodizing for improving corrosion behavior, gaining knowledge on corrosion mechanisms taking place in Al alloys in RR environment and developing methods to improve corrosion resistance.

HLO2: Validate the use of sub-size specimens to monitor the radiation-induced embrittlement of Al alloys in the surveillance programs of RRs

In order to achieve this high-level objective, SO5 and SO6, defined below, are needed. Within these SOs, a through interaction between experiments and numerical simulations based on Finite Element Modelling (FEM) is envisioned.

SO5: FEM study of specimen size effect on fracture toughness initiation and propagation on as-received and irradiated Al alloys

Activities planned: FE simulations, based on standard plasticity and micromechanical modelling of ductile fracture, will be used to investigate the effect of the size (standard and sub-sized) of CT specimens on the critical fracture toughness, which corresponds to the initiation of ductile fracture. In a second step, the specimen size effect on the full crack resistance curve will be evaluated. The modelling framework will be applied to the 6061-T6 alloy, for which input in the form of material laws at virgin and irradiated state are available.

Expected outcome: Determination of size–effect correction factor, validation of use of sub-sized specimens to evaluate FT and tensile properties of RRs Al alloys for surveillance programs.

SO6: Experimental investigation of irradiation embrittlement of several RR Al alloys using sub-sized specimens

Activities planned: Tensile and fracture toughness testing using sub-sized specimens, performed on three Al alloys (6061-T6, 5154-O and 5051), in both as-received and irradiated conditions. Irradiated specimens derived from experiments conducted over a wide range of thermal fluences. The data produced will be capitalized in a dedicated database that will be used to develop and validate FEM simulations supporting size effect assessment.

Expected outcome: Validate experimentally the results obtained in SO5, quantification of any size effect by comparing data obtained with full-size and sub-sized specimens.

HLO3: Enhance the ageing management of the existing RRs to support their continuous safe operation (CSO)

The SO7-SO9, defined below, are required for HLO3 to be completed. These SOs have many intersectional aspects, therefore, a combined list of expected outcomes is presented.

SO7: Comparison of the national rules and codes, the presently used practices dealing with safety and ageing management of the RRs to determine and fill the gaps

The ageing management practices of the participating RRs and the know-how from the institutes that carried out design activities and aging studies for RRs are the base for SO7.

Activities planned: Collection of the existing ageing management methods and know-how experience from RR institutes, suggestion of extension of authority guides (if required), identification of best practices on ageing management and structural integrity of SCCs of RRs.

SO8: Elaborate recommendations to the National Regulatory Committees regarding the upgrade of RRs safety rules and guidelines

Activities planned: Based on the knowledge collected during the Magic-RR project, recommended guidelines of ageing management for RR operators (including periodic check of structural integrity), and a possible list of recommendations for the extension of the RR safety rules to the National Safety Authorizes will be provided.

SO9: Initiate European level research program on ageing and structural integrity of RRs for EU excellence and competence development

The European level research program allows continued long-term research on this topic, exchange of best practices in ageing management, harmonization of ageing management procedures of RRs and provides opportunity to young researchers for competence development.

Activities planned: Form End User Group (EUG) with various RR stakeholders, involving RR operators, regulators and experts for increased collaboration on ageing management of RRs. Organization of workshops with experts from the field and young researchers for competence development.

Expected outcomes SO7-SO9: Determination of existing gaps in the ageing management of the RRs and provide suggestions, harmonization of the ageing methods of the participants, preparation of common guideline to enhance the structural integrity level of RRs, publication of an updated ageing management guideline for the safe operation of existing RRs beyond the designed lifetime, development of EU excellence in the field, education and training of young researchers and competence development.

The Magic-RR project answers the important aspects listed in NRT-01-01: Safety of operating nuclear power plants and research reactors – of the Euratom Work Programme 2023-2025.

4 Methodology

Magic-RR realizes these objectives by leveraging (1) available archive materials and data from the existing research reactors, e.g. from surveillance programs and shut down reactors, (2) operational experience of research reactor operators and (3) advanced characterization and modelling techniques at universities and nuclear research centers. In this section the methodology proposed for the Magic-RR project is presented (see Figure 1).

4.1 Unique set of materials

The proposed work in the Magic-RR project can be kick-started because of the large amount of preparatory work that was performed by the partners and form their national research programs. In fact, a variety of highly irradiated materials from surveillance specimen from the HFR in Petten (5154-O), AA6061 (neutron irradiated & Si-implanted) from CEA, BKR reactor archive materials (AlMg1Si (5051) and AlMg2.5Si (5052)) and highly irradiated 5052-O grade from NRU reactor are available to be distributed and studied among the participating partners. In addition, irradiations in the HFR Surveillance capsule (known as SURPISE-02) are being performed on 6061-T6 alloy to study the abrupt reduction in fracture toughness of the Al alloys at initial stages of irradiation. Especially for the corrosion studies, coupons of 6082 Al alloys have been irradiated in the HFR SUPRPISE-02 facility to investigate the effectiveness of corrosion mitigation and prevention methods such as hydrothermal treatments and anodizing.

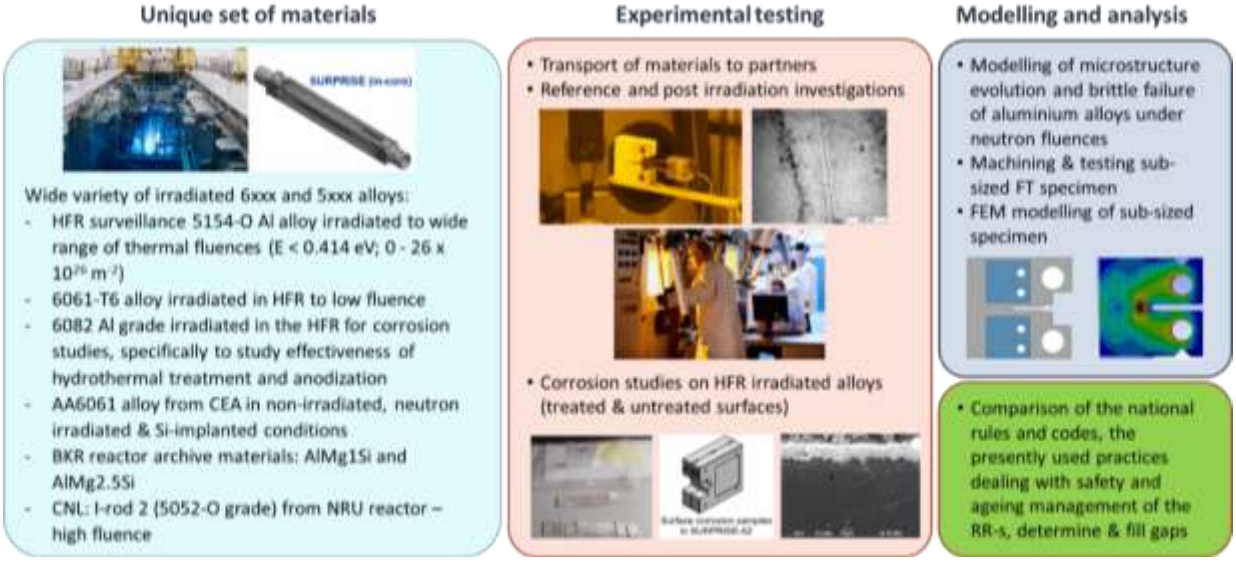

Figure 1. Methodology applied in Magic-RR project.

4.2 Experimental testing

Testing of mechanical properties

The available mechanical properties of irradiated Al alloys in literature are limited. Magic-RR aims to obtain the mechanical properties (tensile, hardness, fracture toughness) by means of an extensive PIE campaign on the above-mentioned materials. The mechanical tests will be performed in the hot cells of the participating partners. The mechanical tests planned within the Magic-RR project are:

- Tensile, notch tensile, hardness testing on reference & irradiated RR materials (AlMgSi and AlMg2.5 alloys, 6061-T6 alloy irradiated in HFR to low fluences)
- In-situ SEM tensile testing (micro and meso-scale) and micro-pillar compression testing
- Nanoindentation using different tip geometries and micron-scale testing of FIB-milled structures as a function of temperature.

Microstructural investigations & correlation with mechanical properties

Changes in the microstructure of the RR materials, as the result of neutron irradiation, will be studied. More specifically, Magic-RR aims to enhance the current understanding of the solute redistribution (in particular Si atoms, coming from transmutation as well as dissolution of β'' precipitates in AA6061-T6) as function of neutron fluence. The new phase formation and segregation on defects (loops, cavities, grain boundaries) will be studied, as well as the thermal recovery of the irradiation-induced damaged microstructure by means of in-situ TEM studies. Solute precipitation and segregation as a function of fluence will be investigated by APT. For example, particularly interesting will be, to study the behavior of the transmutation Si in the Al-alloys for the high fluence regime. Once all Mg present in the matrix is consumed to form Mg_2Si precipitates, Si atoms could start decorating grain boundaries leading to grain boundary weakening. In addition, the effect of the initial bulk composition on the irradiation damage will be investigated. Finally, best-practice methodology for atom probe tomography characterization of irradiated Al-alloys will be developed by applying this characterization technique to at least one common sample by two partners. Finally, the changes in the microstructure will be correlated to the mechanical properties of the alloys as a function of fluence value.

Study of the corrosion behavior of Al alloys during operation conditions and evaluate the effectiveness of prevention and mitigation strategies

The corrosion behavior of Al alloys during operation conditions of RRs and the effectiveness of mitigation and prevention strategies such as anodization and thermal treatments will be studied. Samples (with and without surface treatments) have been irradiated in the SURPRISE irradiation facility of the HFR (Figure 2). The surfaces of these coupons are exposed to the water of the reactor pool.

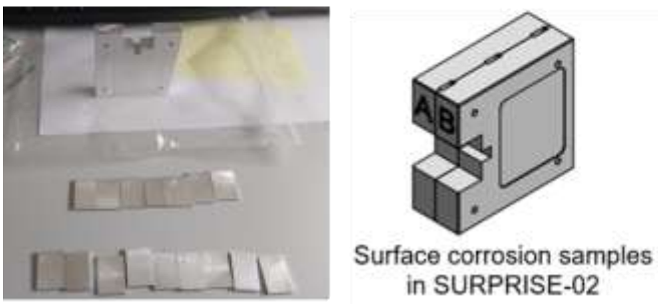

Figure 2. Picture and drawing of the corrosion specimens irradiated in the SURPRISE irradiation facility of the HFR

Hydrothermal treatments and anodization of Al alloys will be performed and the corrosion resistance of treated and untreated Al alloys under irradiation will be investigated.

SEM/EDX analysis of the surfaces before and after the corrosion test will be carried out to identify the corrosion morphology and obtain insight into the corrosion mechanism and its possible relation with the microstructure of the alloys. If it is necessary for more quantitative analysis of the chemical composition of the corrosion products, XPS analysis will be carried out.
SKPFM will be applied to obtain surface potential maps at the sub-micrometer scale to elucidate the reactivity differences between microstructural features, especially intermetallic phases, and segregates for identifying the initiation sites of corrosion.

4.3 Modelling and analysis

Modelling of microstructure evolution and brittle failure of aluminum alloys under neutron fluence

Within Magic-RR, a framework for modelling of microstructure evolution under neutron irradiation, and the irradiation hardening and embrittlement due to this microstructure evolution under general mechanical loads will be developed. A multi-scale approach will bridge from the physical processes that occur at the scale of the crystalline lattice and its defects, to mechanical failure at the macroscopic application scale. A combination of modelling techniques will be employed, including a cluster dynamics model, crystal plasticity and a probabilistic brittle failure model (see Figure 3). The modelling framework will be applied to a selected aluminum alloy, for which input in the form of characterization of microstructures due to various neutron loads, and results of mechanical experiments are available from project partners.

Using a cluster dynamics type model [17, 18, 19, 20, 21, 22, 23, 24], compositional changes due to transmutation processes and lattice damage evolution are modelled. In particular, transmutation of Al to Si and the formation and evolution of Mg_2Si precipitates are captured. Additionally, grain boundary decoration by Si is accounted for, which is crucial for grain boundary integrity. The diffusional processes determining the kinetics of precipitate evolution and grain boundary decoration are affected by the neutron-induced lattice damage. The model is characterized and validated using available experimental data for the material.

In the next step, a full-field micromechanical model of the polycrystalline structure of the material is developed. For this purpose, a finite element representative volume element (RVE) of the microstructure is created based on available data from experimental microstructure characterization [19, 20, 23]. At a material point level, a temperature-dependent crystal plasticity model is used, of which the slip law will be enriched by precipitation hardening effects, accounting for the influence of the Mg_2Si precipitates. With this approach, the effect of neutron irradiation on the evolution of the mechanical response and grain boundary loading are captured.

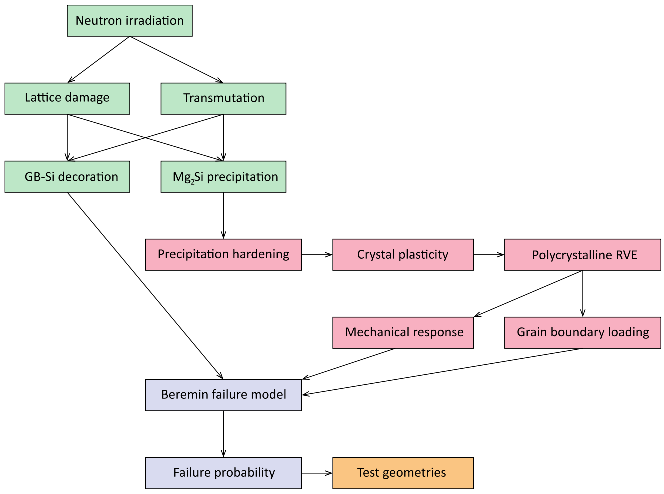

Figure 3. Modelling of microstructure evolution and brittle failure of aluminum alloys under neutron irradiation

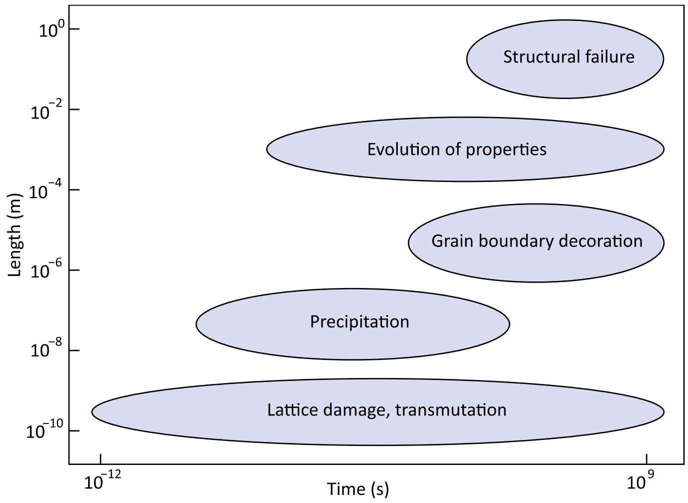

Figure 4. Length-scales and timescales involved in microstructure evolution and brittle failure of aluminum alloys under neutron fluence.

Using a probabilistic approach [20, 23, 24], based on the local and global RVE response, a failure probability analysis is obtained. This approach accounts for the competition and interplay between different processes, each with their own length-scales and timescales (see Figure 4), including irradiation hardening due to transmutation-induced precipitation and decrease of grain boundary integrity due to Si-decoration. This failure analysis is then upscaled to mechanical test geometries, allowing for a validation of the modelling framework with available experimental data for different loads and test conditions.

Investigation of the applicability of sub-sized specimen for evaluating mechanical properties of Al alloys

Sub-size specimens will be manufactured in hot cells from remnants of irradiated RR surveillance samples. Sub-size CT specimens (0.4T &0.16T-CT) will be manufactured from broken irradiated 1T-CT & 0.5T-CT specimens (standard Compact Tension specimens with 25 mm and 12.5 mm thickness respectively) by electrical discharge machining (EDM) and by using a CNC milling machine. Pin holes will be machined by drilling.

The experimental task will be divided in two parts:

1. Assessment of hardening based on sub-sized tensile specimens (5154 and 5051 alloys). Tensile specimens (smooth and notched) will be used to perform tensile testing. Sub-size tensile test results will be compared with surveillance data on larger specimens.
2. Assessment of fracture toughness based on sub-size CT specimens. Fracture toughness determined using sub-size CT specimens will be compared with data obtained on standard CT specimens. Fracture toughness values from standard CT specimens are already available for irradiated 6061-T6 and 5154-O Al alloys (CEA and NRG). For as-received and irradiated 5051, HUN-REN-CER will perform fracture toughness tests on sub-size as well as standard specimens for the comparison.

In addition, simulation of standard and sub-size CT specimens will be performed in order to evaluate the effect of size on the ductile fracture initiation toughness, which is a property that may be influenced by the reduction of specimen size. Finite element simulations based on standard plasticity as well as on micromechanical modelling of ductile fracture will be combined to provide accurate assessment of the size effect on the critical fracture toughness that correspond to the initiation of ductile facture. In a second step, the size effect on the full crack resistance curve ($J-R$ curve, which is a curve describing the evolution of the energy released "J-integral" as a function of crack extension "Δa") will be evaluated.

Non-linear finite elements modelling (FEM) will be performed on sub-size CT specimens as well as on 0.5T-CT specimens. The design of the sub-size CT specimen will be studied and validated. Size effect on local mechanical fields, the resistance curve and the fracture toughness at crack initiation will be assessed. A dialogue with experimental results on both types of specimens will be set up in order to quantify a size–effect correction from the finite element simulations based on physically-based modelling.
Evaluation of the size effect on the critical fracture toughness will be based on elasto-plastic flow theory whereas ductile damage behavior will be used to study the size effect on the $J-R$ curves. Previously established material laws will be used. These laws have been validated for the simulation of plastic and damage behavior of the non-irradiated as well as the irradiated Al 6061 alloy that will be tested.

Enhancement of the ageing management of the existing RRs to support LTO

The work will start with the collection of ageing management practices of the participating research reactors, and information from the institutes working in design or ageing studies for research reactors, and it will be extended with the available information from the literature. To enhance the ageing management and the mitigation of the ageing damage, the existing literature will be summarized and evaluated, and it will be extended by the results obtained in Magic-RR. Based on the collected knowledge, the existing safety and ageing management practices will be evaluated to assess whether they can be directly used for operation beyond the design lifetime or require upgrading.

5 Expected results and impact

The results of Magic-RR will provide (a) improved mechanistic understanding and new data on irradiation induced transmutation damage of aluminum alloys, (b) advanced multi-scale modelling tools for improved prediction of irradiation damage, (c) new insights on corrosion damage and mitigation methods and prevention strategies for corrosion in RR environment, (d) validation of sub-sized fracture toughness testing of Al alloys for surveillance programs and (e) enhanced ageing management methods to support the continued safe operation (CSO) of existing research reactors. This new knowledge enables European excellence in research reactor materials expertise, which includes better design of reactor vessel and core structures of new RRs; application of sub-size specimen testing for surveillance test programs of existing European RRs (where there is only limited availability of surveillance specimens), availability of well characterized PIE data to validate multi-scale models to predict irradiation damage; and transfer of this knowledge to a younger generation of nuclear scientists and staff at nuclear organizations. Ultimately, this will help to support utilities in CSO license renewal while meeting increased safety regulations, and to support regulators and TSOs with improved prediction tools and understanding of damage mechanisms in safety relevant structures for CSO of European RRs. Eventually CSO of existing RRs help in (i) continued supply of medical isotopes for cancer treatment and diagnosis and (ii) irradiation testing and qualification of new materials and fuels, which is typically carried out in RRs. Magic-RR seeks to engage with the following target groups, namely RR operators, new RR developers, regulators, scientific community, and public to maximize its impact (see Table 1). An overview of expected impact areas of the Magic-RR project is summarized in Figure 8.

Figure 8. Impact areas of Magic-RR project

Table 1. Outcomes and impacts

Target groups	Outcomes	Impacts
Research reactor operators (End User Group Members)	• Crucial data on irradiation damage of critical safety relevant structures to support CSO of RRs • Physics based models for prediction of influence of irradiation damage and fracture of RR Al alloys • Application sub-size specimens for surveillance testing is validated	• Safe continued operation of RRs (HFR, BR-2, Budapest research reactor) • Supports effective execution of surveillance testing for all RRs (Save costs and time) • Uninterrupted supply of medical isotopes • Continued European research on qualification of new materials fuels for advanced reactors
New research reactor developers (End User Group Members	• Improved design of new RRs through better selection of materials for critical structures • Reduce the cost and increase effectiveness of surveillance program by application sub-size specimens	• Licensing of new RRs (PALLAS and JHR) • Improved safety of new RRs • Reduced radioactive active waste • Increase operational efficiency and Reduce reactor outage time
Regulators	• Improved assessment of materials ageing • Improved methods for structural integrity of RRs	• Safe RRs through improved understanding of ageing and degradation mechanisms of materials • Ensure compliance with European Safety Direct and other international standards
Scientific community (Nuclear materials, Irradiation effects, Modelling, and simulation)	• Deeper understanding and new data on irradiation induced transmutation damage of aluminum alloys • Development of advanced multi-scale modelling approaches for prediction of irradiation induced damage in Al alloys • New insights on corrosion damage of research reactor materials • 2 PhD students, and a post-doc are trained	• EU Excellence and innovation capacity. • International publications on newly discovered irradiation induced damage mechanism, corrosion effects and damage prediction models in high citation index journals. • Bringing of knowledge gaps and transfer of knowledge from retiring experts to nee generation

6 Project organization

The Magic-RR consortium includes 12 participants from 6 different countries, namely The Netherlands, France, Hungary, UK, Canada and South Africa (see Table 2). The consortium partners have the required competences and facilities to successfully execute the planned tasks as shown in Table 3. The Magic-RR project is organized into 5 work packages (WP1-WP5) to achieve the forementioned objectives. All the technical work is planned in 3 work packages (WP1-WP3). WP4 is dedicated for communication, dissemination, education, and training activities. Project management and scientific advisory board activities will be performed in WP5. Specifically, WP1 is dedicated to performing the reference and PIE testing, microstructural characterization of selected Al alloys used in RRs, corrosion testing and multiscale modelling of irradiation damage in Al alloys. The results will be directly useful to achieve the specific objectives 1 and 4 (SO1 & SO4). WP2 is focused on an experimental – numerical approach for validation of sub-size specimens for surveillance testing of RRs to achieve SP5 and SO6. WP3 is focused on ageing management methods of RRs. The results produced in WP1 and WP2 together with information on ageing management methods collected from participating RR operators and EUG members will be analyzed in WP3 to produce an updated ageing management guide to support continued safe operation of existing RRs. The results from WP3 will help achieving the SO7-SO9. Total WP structure of Magic-RR project and interconnection between different WPs are shown in a PERT chart in Figure 10.

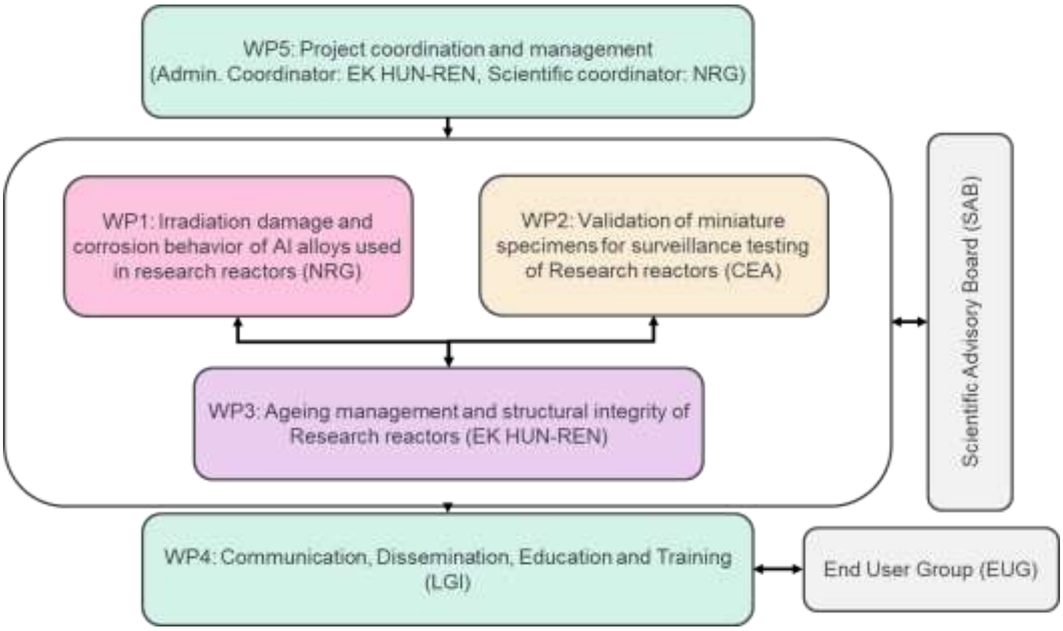

Figure 10. PERT chart showing WP structure of Magic-RR Project

Table 2. List of participants

Participant #	Official name	Short name	Country
1 (Administrative coordinator)	Energiatudomanyi Kutatokozpont	HUN-REN-CER	HU
2 (Scientific coordinator)	Nuclear Research and Consultancy Group	NRG	NL
3	Centre National de la Recherche Scientifique CNRS	CNRS	FR
4	Universite de Rouen Normandie	UR	FR
5	Eindhoven University of Technology	TUe	NL
6	Commissariat a L'Energie Atomique et aux Energies Alternatives	CEA	FR
7	University Of Oxford	Oxford	UK
8	United Kingdom Atomic Energy Authority	UKAEA	UK
9	Canadian Nuclear Laboratories LTD	CNL	CA
10	Delft University of Technology	TUD	NL
11	LGI Sustainable Innovation	LGI	FR
12	The South African Nuclear Energy Corporation Limited	NECSA	ZA

Table 3. The key partner competencies in Magic-RR

		Expertise								
Organization type	**Partner**	**Reference materials testing**	**PIE testing**	**Small specimen testing**	**Numerical modeling**	**Advanced Microscopy**	**Corrosion**	**Structural integrity and ageing management**	**Education and Training**	**Management and Communication**
Nuclear R&D organizations	HUN-REN-CER	■	■	■	■	■		■	■	■
	NRG	■	■	■	■	■	■	■	■	■
	CNRS	■	■	■		■			■	
	CEA		■	■	■				■	■
	CNL	■	■	■		■		■		
	UKAEA	■	■	■						
RR Operators	NRG	■	■	■	■	■	■	■	■	■
	HUN-REN-CER	■	■	■	■	■		■	■	■
	TUD	■				■	■			
	NESCA							■		
Universities	UR	■	■	■		■			■	
	Oxford	■	■	■		■			■	
	TU/e	■		■	■	■			■	
	TUD	■		■	■	■	■		■	
SME	LGI									■

Conflicts of interest

The authors declare that they have no competing interests to report.

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This article has no associated data generated and/or analyzed.

Author contribution statement

M. Kolluri: Conceptualization, Methodology, Writing - Original Draft, Funding acquisition, Project administration, Resources, **F. Naziris:** Conceptualization, Methodology, Funding acquisition, Project administration, Writing - Review & Editing, Resources, **B. Tanguy:** Funding acquisition, Resources, **P. Francois:** Writing - Review & Editing, Funding acquisition, Project administration, Resources, **F. Gillemot:** Funding acquisition, Writing - Review & Editing, **I. Szenthe:** Project administration, Resources, **J. A. W. van Dommelen:** Writing - Review & Editing, Resources, **Y. Gonzalez-Garcia:** Resources, **B. Radiguet:** Resources, **P. Bagot:** Resources, **A. London:** Resources, **H. Namburi** Resources, **J. Mostert:** Resources

Export control note

The content within this document is classified with the code EU DuC = N. EU DuC means European dual use code.

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