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Preliminary assessment of GFR decommissioning by design issues

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EXECUTIVE SUMMARY

This deliverable provides an overview of the key decommissioning considerations for a Gas Cooled Fast Reactor (GFR) within the TREASURE project. As no GFR-specific international decommissioning standard currently exists, the analysis is based primarily on IAEA safety requirements and guidance, complemented by experience from fast reactor and gas-cooled reactor programmes, as well as relevant Euratom, OECD NEA and WENRA frameworks. The document aims to support early integration of decommissioning aspects into reactor design and lifecycle planning, ensuring alignment with international good practice and regulatory expectations.

Internationally applied decommissioning strategies are reviewed, with immediate dismantling identified as the most suitable reference approach for the ALLEGRO GFR concept. This strategy enables early risk reduction, effective use of operational knowledge and existing systems, and avoids long-term uncertainties associated with deferred dismantling. The deliverable identifies key reactor construction materials relevant to decommissioning—particularly activated steels, concrete and ceramic components—and outlines the main technical phases of GFR decommissioning, highlighting specific challenges related to fast-neutron activation, high-temperature materials, dust-forming ceramics and the absence of liquid coolant systems for chemical decontamination.

The document also emphasises the importance of safeguards and security throughout decommissioning due to the high plutonium content typical of fast-reactor fuels. Maintaining material accountancy, traceability and adequate physical protection is essential during dismantling, waste management and site release. Overall, the deliverable concludes that early consideration of decommissioning requirements is critical to ensuring safety, regulatory compliance and long-term cost efficiency, and provides a sound basis for more detailed decommissioning planning as the ALLEGRO GFR concept evolves.

CONTENT

1 INTRODUCTION

The purpose of this deliverable is to provide a structured and comprehensive overview of the decommissioning considerations relevant to Helium Cooled Fast Reactor (GFR) within the TREASURE project framework. Because no dedicated international standard exists specifically for GFR decommissioning, the document synthesises relevant requirements, guidance, and operational experience drawn mainly from IAEA safety standards and guides. These sources collectively form the applicable regulatory and technical foundation for developing safe, effective and harmonised decommissioning strategies.

The deliverable outlines the main strategic approaches used internationally, with emphasis on immediate dismantling as the reference strategy in alignment with widely accepted IAEA recommendations. It further identifies key reactor construction materials relevant for decommissioning planning and provides a step-by-step overview of the technical phases associated with decommissioning a GFR, taking into account the specific challenges linked to high-temperature materials, fast-neutron activation, helium coolant systems and ceramic or refractory components. Additional attention is given to expected end states and the safeguards and security measures that must be maintained due to the plutonium-bearing fuels commonly used in fast reactors.

The document is intended to support early consideration of decommissioning aspects within the TREASURE project, ensuring that design choices, safety approaches, material selection and lifecycle planning are consistent with international good practice. It also provides a baseline for future, more detailed decommissioning planning as the reactor concept is further defined.

2 APPLICABLE FRAMEWORK

The assessment of this project from the point of view of decommissioning will be based on the IAEA materials listed in Resources. The reason for this is their more detailed processing, greater scope and wider use.

2.1 IAEA

The IAEA does not publish a single "GFR specific" decommissioning standard. Instead, decommissioning of a Gas Cooled Fast Reactor follows:

1. **Generic decommissioning safety requirements**
    - GSR Part 6 – Decommissioning of Facilities (mandatory requirements)
    - SSG 47 – Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities (practical guidance)
    - NW-G-2.1 - Policies and Strategies for the Decommissioning of Nuclear Facilities
2. **Fast reactor–specific experience**
    - IAEA TECDOC 1405 – Operational and decommissioning experience with fast reactors
    - IAEA TECDOC 1633 – Decommissioning of fast reactors (methodological lessons, waste characterization, strategy development)
3. **Gas cooled related experience**
    - IAEA TECDOC 1043 – Technologies for gas cooled reactor decommissioning, fuel storage and waste disposal

2.2 Other organisations

2.2.1 EURATOM

EU decommissioning guidance is shaped mainly through Euratom regulations and directives, which set safety, waste-management and funding requirements for decommissioning projects across Member States.

A key example is Regulation (Euratom) 2021/100, which establishes an EU financial and knowledge-sharing framework to support safe decommissioning of facilities in Bulgaria, Slovakia, and at several JRC sites. It mandates progress reporting, safety and waste-management indicators, and dissemination of decommissioning knowledge across Member States.

EURATOM directives on nuclear safety and on spent fuel/waste management also structure national responsibilities and require high regulatory standards throughout decommissioning.

2.2.2 OECD NEA

The OECD Nuclear Energy Agency (NEA) provides several technical and regulatory publications addressing decommissioning strategy, safety, and international good practices.

The report "Regulating the Decommissioning of Nuclear Facilities: Relevant Issues and Emerging Practices" (NEA No. 6401) reviews regulatory challenges, evolving practices, and international coordination in decommissioning oversight.

The NEA also publishes practical guidance and case-study collections through its Working Party on Decommissioning and Dismantling (WPDD), highlighting global experience, waste routing, dismantling methods, and site release practices.

2.2.3 WENRA

The Western European Nuclear Regulators Association (WENRA) issues harmonised Safety Reference Levels (SRLs) for decommissioning, widely used by European regulators.

Its Working Group on Waste and Decommissioning (WGWD) develops SRLs covering strategy, planning, conduct of decommissioning, safety verification, waste management, emergency preparedness, and licence termination.

The most up-to-date consolidated document is the WENRA Decommissioning Safety Reference Levels, Version 2.3 (January 2024), which details safety management, planning requirements, safety case expectations, monitoring, organisational responsibilities, and benchmarking results from national implementation.

3 OVERALL DECOMMISSIONING STRATEGY

The IAEA recommends a graded, phased approach justified by safety assessment, regardless of reactor type.

3.1 Decommissioning strategies

3.1.1 Immediate Dismantling

Also known as (DECON). Immediate dismantling means that decommissioning activities begin as soon as practicable after permanent shutdown, rather than delaying them for decades.

Key Features

- Early transition to decommissioning
- Active use of existing plant systems
- Higher worker doses in some areas, but manageable
- Early characterisation and removal of contaminated components
- Waste processing occurs during the dismantling campaign

Advantages

- Regulatory and public assurance through early risk reduction
- No need to maintain a site for decades
- Retention of institutional knowledge
- Utilisation of intact systems
- Earlier site release for reuse

Challenges

- Earlier site release for reuse
- Higher initial radiation fields
- Large workforce needs over a short time
- Waste management infrastructure must be ready
- More complex dose optimisation

3.1.2 Safe Enclosure / Deferred Dismantling

Formerly known also known as SAFSTOR. After shutdown, the facility is placed into a long-term safe enclosure (typically 30–60 years) to allow radioactivity to decay before starting dismantling.

Key Features

- Structural maintenance and surveillance required for decades.
- Lower dose rates and easier dismantling after decay.

Advantages

- Reduced radiation exposure to workers.
- Smoothing out financial and logistical constraints.
- Useful if waste disposal routes are not immediately available.

Challenges

- Institutional control must be maintained for decades.
- Future workforce and funds must be guaranteed.
- Potential aging of structures may complicate later dismantling.

3.1.3 Entombment

Also known as In-situ Disposal. The radioactive parts of the facility are encased in a durable structure (e.g., concrete) and left until radioactivity decays to a level permitting unrestricted or regulated use. IAEA notes this strategy is not recommended for reactors under normal circumstances, limited to:

- Severe contamination (e.g., accident-damaged reactors).
- Situations where dismantling is technically impossible.
- Small facilities with very low remaining inventory.

Challenges

- Long-term institutional control (potentially centuries).
- Requires extremely robust structures and monitoring.

3.2 Strategy selection

According to GSR Part 6, the strategy must be chosen early, justified, and documented as part of the Decommissioning plan. Selection must consider:

Protection of people and environment

- Minimise radiological doses
- Apply ALARA principles
- Reduce long-term burdens

Technical feasibility

- Availability of technologies
- Site-specific constraints
- Radiological and physical conditions

Waste management infrastructure

- Interim storage

- Final disposal routes
- Availability of processing facilities

Financial resources

- Secured funding mechanism
- Cost estimates for entire lifecycle

Regulatory requirements

- Licensing pathways
- Clearance levels
- Environmental impact assessment

Societal, stakeholder, and policy factors

- National strategy
- Local community expectations
- Long-term land-use planning

4 KEY GFR REACTOR CONSTRUCTION MATERIALS RELEVANT FOR DECOMMISSIONING

From the supporting materials that are currently available for the project, it is not possible to determine exactly what materials and how much will be used. We can only infer the basic components of the device and the likely materials used. The supporting materials only mention steel, concrete, zirconium alloy and helium as a cooling medium.

4.1 Steels

4.1.1 Carbon and low alloy steels

Reactor pressure vessel (RPV), primary circuit piping, support structures.

Decommissioning impact:

- Subject to neutron activation, producing radionuclides such as Co-60, Fe-55, Ni-63, Ni-59 and occasionally Nb-94.
- Represent the core of activated metallic waste.
- Large and heavy components require underwater segmentation, mechanical cutting, or diamond-wire techniques.
- Waste typically classified as low and intermediate level waste (LILW), with some fractions eligible for very low-level waste (VLLW) after radiological characterisation.

4.1.2 Stainless steels

Internal RPV components, heat exchangers, primary system valves and piping.

Decommissioning impact:

- Higher Ni and Co content higher long-term activation (notably Ni-59 and Ni-63).
- Often show the highest dose rates during dismantling.
- Difficult to cut and handle; fragmentation usually required.
- Forms an essential part of activated structural waste.

4.2 Concrete and shielding materials

Biological shielding, containment structures, reactor basements.

Decommissioning impact:

- Neutron activation in the first layers results in Eu-152, Eu-154, Co-60, H-3.
- May contain deep contamination from liquids, leakages, or aerosols.
- Represents the largest volume of decommissioning waste.
- Usually categorised as VLLW or LLW (low level waste), depending on activation depth.
- Graphite (if present) –

    - Contains long lived radionuclides (C-14, Cl-36, H-3).
    - Dust formation and potential pyrophoric behaviour require controlled dismantling and inert environments.
    - Large volumes and absence of widely accepted disposal routes make graphite a strategic long-term challenge.

4.3 Silicon-carbide (SiC)

Fuel cladding, structural components

Decommissioning impact:

- Stability and lower activation compared to metallic cladding
- High resistance of SiC to oxidation and corrosion at high temperatures
- Less likely to release significant amounts of fission products into the reactor coolant
- Slight contamination of the outer surface of the cladding
- Ceramic nature poses a challenge during the physical dismantling of the fuel rods, requiring techniques that prevent the creation of radioactive dust or fuel debris

4.4 Aluminium alloy

Heat exchangers, auxiliary components, experimental loops.

Decommissioning impact:

- Activate to Na-22, contributing to short- to medium-lived waste streams.
- Strongly affected by corrosion; may produce contaminated sludge.
- Cutting under water can produce hydrogen, requiring safety measures.

4.5 Polymers, cables and insulation materials

Cable insulation, gaskets, seals, filtration media.

Decommissioning impact:

- Generally contaminated rather than activated.
- Often constitute a large share of non-metallic LLW.
- Halogenated plastics (e.g., PVC) need controlled handling or avoidance of incineration due to potential toxic by-products.
- Efficiently trap radioactive aerosols and corrosion products.
- Low density but high volume → costly transport and conditioning.
- Typically treated as LLW or VLLW, depending on contamination.

4.6 Control system and coolant

Decommissioning impact:

- Absorber material - B4C. Unlike materials like cadmium or hafnium, B4C absorbs neutrons without forming significant quantities of long-lived radionuclides. This makes it safer for long-term handling and disposal. Helium as a coolant
- Helium does not become activated by neutron irradiation, eliminating the need to manage radioactive liquid or gas coolant during decommissioning.

5 KEY TECHNICAL PHASES FOR A GAS COOLED FAST REACTOR

5.1 Final shutdown and transition to decommissioning

Stabilize the plant, remove decay heat, place systems in safe configuration.

Key task:

- Rapid cooldown from high outlet temperatures (650–850 °C for GFR concepts).
- Isolation of helium coolant systems.
- De-energizing high-temperature blowers or circulators.
- Initial radiological characterization of reactor cells.

Helium produces no activation corrosion products, but fast neutron spectra cause heavy activation of structural materials (SiC/SiC composites, refractory metals).

5.2 Removal of fuel and core internals

This is the most safety-critical phase in GFR decommissioning.

Key tasks:

- Defuel the reactor vessel (ceramic-matrix or refractory-metal fuel).
- Removal of control rods, absorber assemblies, and reflectors.
- Packaging spent fuel into shielded transportation or storage casks.

Specific challenges

- High decay heat density in fast-spectrum fuel.
- composite cladding – risk of fragmentation during extraction.
- Potential for high-temperature helium contamination with activated particulates.
- Some GFR designs use vented fuel → possible residual fission gas in circuits.

5.3 Coolant system deactivation and primary circuit decontamination

Even though helium is inert, the primary circuit is highly activated due to fast neutrons.

Key tasks:

- Depressurization and inerting of helium loops.
- Filter and trap activated dust (e.g., Co-60, Fe-59, Co-58).
- Seal or dismantle primary heat exchangers, ducts, and circulators.
- Remove impurity traps containing activated charcoal/sorbents.

Specific challenges:

- No water, no chemical decontamination; require dry decontamination techniques (abrasive blasting, foam, remote mechanical tools).
- High activation of graphite (if used in reflectors) and silicon carbide.

5.4 Dismantling of reactor vessel and internals

After cooldown and decontamination, dismantling proceeds.

Key tasks:

- Cutting and segmenting the reactor pressure vessel (RPV).
- Removing core support structures, neutron shield blocks, and reflectors.
- Handling large SiC/Ceramic components (brittle, dust-generating).

Specific challenges:

- Highly activated structural materials due to fast neutron flux.
- High-temperature refractory steels complicate segmentation.

5.5 Secondary systems and balance-of-plant dismantling

Key tasks:

- Turbine island removal (if direct Brayton cycle).
- Removal of intermediate heat exchangers (IHX) for indirect cycles.
- Dismantling of helium purification, compressors, blowers.
- Removal of decay-heat exchangers and emergency cooling systems.

Specific challenges:

- High-temperature piping requires abrasive/thermal cutting with dust containment.

5.6 Management and disposal of activated materials

GFRs generate large quantities of high-activation waste.

- Main waste streams
- Composite cladding, intermediate- or high-level waste expected
- Highly activated vessel steels (Ni-rich alloys, ODS steels).
- Ceramic insulators, reflector blocks, control rod guide tubes.
- Contaminated filters or traps from helium purification systems.

Specific challenges:

- No established disposal pathways for SiC nuclear waste in most countries.
- Fast-reactor-grade steels have long-lived activation products (e.g., Ni-59, Nb-94, Co-60).

5.7 Final site cleanup, survey, and release

Key tasks:

- Removal of remaining civil structures or their decontamination.
- Final characterization of soils, drainage, ventilation shafts.
- Verification that clearance levels comply with national regulations.

- Regulatory release of the site (unrestricted or restricted).

Specific challenges:

- Activation of biological shield concrete can be higher due to fast neutrons penetrating deeper.
- Hot cells for fast-reactor fuel handling require additional decontamination.

6 EXPECTED END STATE

According to current accepted practice, the final goal is:

- Release of the site from regulatory control, back to the freely usable greenfield
- Conversion to another licensed nuclear facility

This requires:

- Final radiological survey
- Regulatory confirmation
- Archival of decommissioning records for future

7 SAFEGUARDS AND SECURITY ASPECTS

7.1 Safeguards Aspects

GFR reactor frequently use Pu rich fuel (e.g., MOX, U PuC), which makes safeguards a central part of decommissioning.

Spent Fuel Safeguards

Fuel contains high plutonium content and good isotopic quality what makes it attractive for possible diversion.

Special Nuclear Material (SNM) During Dismantling

- debris containing plutonium
- contaminated structural materials,
- fine powders from ceramic fuels.

Safeguards must address:

- segmentation under surveillance,
- measurement of alpha-bearing waste,
- traceability of waste containers,
- maintaining tamper-proof records and seals (e.g., IAEA VACOSS, COBRA seals).

Measurement Challenges

- are high-density and strong absorbers,
- require calibrated NDA methods, often calorimetry + gamma spectrometry.
- early sampling campaigns,
- pre-dismantling nuclear material verification,
- design information verification before decommissioning activities change facility configuration.

7.2 Security Aspects

Nuclear security during decommissioning shifts focus from operational protection to SNM control and site vulnerability management.

Physical protection of Nuclear material

- high quantities of weapons-usable plutonium,
- compact, ceramic fuel pins that are difficult but not impossible to misuse,
- high-category storage, protection on depth
- armed response
- protected transport routes for removed fuel

Security of Radioactive Waste

- high activity expected - long lived activation products
- high-category of radioactive material, protection on depth
- robust container tracking,

8 CONCLUSIONS

This deliverable presents an integrated assessment of the main strategic, technical and regulatory factors relevant to the decommissioning of the proposed Gas Cooled Fast Reactor, using internationally recognised IAEA standards as the primary reference. While GFR-specific decommissioning experience remains limited, the combined body of knowledge from fast reactor programmes, gas-cooled reactor operation, and general decommissioning practice provides a solid basis for planning future activities.

The comparison of decommissioning strategies confirms that immediate dismantling aligns best with current regulatory expectations, supports early risk reduction and knowledge retention, and avoids the long-term uncertainties associated with deferred dismantling. The analysis of reactor construction materials highlights the importance of early characterisation and waste-routing consideration, especially for highly activated steels, components and ceramic fuels for which established disposal pathways may be limited. The stepwise breakdown of key technical phases demonstrates that GFR decommissioning presents specific challenges—particularly dust-forming materials, high activation levels and the absence of chemical decontamination options—requiring tailored technologies and robust controls.

Safeguards and security remain essential throughout decommissioning because of the high plutonium content typical of fast reactor fuels. Maintaining material traceability, secure storage, and reliable measurement capabilities is critical for regulatory compliance and non-proliferation objectives.

Overall, the findings emphasise the need to incorporate decommissioning considerations early in the design and planning of the ALLEGRO GFR concept. Doing so will ensure regulatory alignment, optimise long-term safety and cost efficiency, and support the eventual safe release or reuse of the site at the end of the facility's lifecycle.

Resources

1. SAFEG D1.3 *Assessment of Proliferation Resistance of ALLEGRO Spent Fuel Reprocessing Technology.* 2022
2. IAEA General Safety Requirements Part 6 – Decommissioning of Facilities, IAEA Vienna 2014
3. IAEA SSG 47 – Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, IAEA Vienna 2018
4. IAEA TECDOC 1405 – Operational and decommissioning experience with fast reactors, IAEA Vienna 2004
5. IAEA TECDOC 1043 – Technologies for gas cooled reactor decommissioning, fuel storage and waste disposal, IAEA Vienna 1998