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Role of Fast Neutrons in Minor Actinide Transmutation and Long-Lived Radioactive Waste Reduction in Lead Cooled Fast Reactor: *A Systematic Review*

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ABSTRACT: The long-term sustainability of nuclear energy relies on the safe management of minor actinides (MAs) and long-lived fission products (LLFPs). The present work aims at systematically evaluating the role of the fast neutron spectrum in the nuclear transmutation of these isotopes in the Lead-cooled Fast Reactors (LFRs) to support the realization of a closed fuel cycle. The present work was performed as a systematic review following PRISMA 2020 guidelines and summarized data from 24 peer-reviewed sources to compare transmutation efficiency and neutronic features. The results indicate that the fast neutrons spectrum in LFRs is a very efficient environment for the actinide destruction by increasing the probability of the fission with respect to the neutron capture. In contrast to thermal reactors, which have positive D-factors and a tendency to accumulate heavier actinides, LFRs have negative D-factors that lead to waste destruction. In particular, an optimal loading of 1.5 wt% MAs provides annual transmutation rates of 15.18% for Am-241 and 13.07% for Np-237 with support ratios larger than one. This configuration is stable for core criticality and neutron flux distribution, but technical challenges remain, including accumulation of Curium isotopes (Cm-244 and Cm-245) and nearly 50% reduction in the effective delayed neutron fraction, affecting safety margins. In conclusion, LFR technology provides clear neutronic benefits for waste reduction over thermal systems but operational strategies should be optimized for curium management and reactor safety to allow evidence-based development of Generation IV reactors for sustainable waste management.

KEYWORDS: Lead-cooled Fast Reactor, Minor Actinides, Nuclear Transmutation, Nuclear Waste, Fast Neutron Spectrum, Closed Fuel Cycle

1. INTRODUCTION

Nuclear energy has become one of the most important low-carbon energy sources to improve energy security, reduce greenhouse gas emissions and support sustainable development over the past decades. The ever-increasing demand for energy worldwide, the depletion of fossil fuel resources and climate change issues have resulted in the development of advanced nuclear technologies as a reliable alternative for electricity generation. Nuclear power plants emit relatively little carbon dioxide in comparison with fossil fuel plants and yet generate large amounts of electricity. However, the safe handling of spent nuclear fuel and radioactive waste, which is a major environmental and technical challenge, remains crucial for the sustainable long-term use of nuclear energy (Abram & Ion, 2008; Grambow, 2022; IAEA, 2018).

A large fraction of the spent nuclear fuel is the Minor Actinides (MAs) group including Neptunium (Np), Americium (Am) and Curium (Cm) that is responsible for a large part of the long-term radiotoxicity, decay heat and storage needs of the radioactive waste. Their long half-lives mean they must be disposed of geologically for long times, complicating and adding to the cost of waste management. The Partitioning and Transmutation (P&T) strategy has been proposed as an effective solution to solve this problem. In this approach, minor actinides are separated from spent fuel and irradiated by an appropriate neutron flux, where they either fission or transmute into shorter-lived or more stable isotopes. Successful implementation of P&T can substantially reduce radiotoxicity, decay heat, and long-term waste inventories while contributing to the realization of a closed nuclear fuel cycle (Grambow, 2022; IAEA, 2018; Salvatores & Palmiotti, 2011; OECD/NEA, 2020; Sun et al., 2023).

The Lead-cooled Fast Reactor (LFR), a concept of Generation IV reactors, has attracted significant interest due to its favorable neutronic and thermal characteristics for transmutation applications. Molten lead has low neutron absorption cross-section, negligible moderation, very high boiling point and excellent heat transfer properties, which allow the fast neutron spectrum to be maintained while improving the inherent safety of the reactor. These features make the LFR a promising technology for supporting a closed fuel cycle and advanced management of radioactive waste. (Alemberti, 2016; Cinotti et al., 2011; Alemberti, 2020).

The fast neutron spectrum is a feature of fast reactors and is important for the transmutation of minor actinides. The fission probability relative to neutron capture is increasing with neutron energy. This allows to transmute long-lived actinides to shorter-lived fission products rather than to heavier isotopes. Thus, fast reactors can reduce the radiotoxicity and volume of long-lived radioactive waste while, at the same time, allowing recycling of fissile materials and the closure of the fuel cycle. Previous investigations have confirmed the importance of fast neutron spectra for improving transmutation performance (IAEA, 2022; Liu et al., 2020; Toshinsky & Petrochenko, 2012).

Recent investigations have demonstrated that the transmutation efficiency of LFRs is strongly influenced by core design, fuel composition, neutron flux, and neutron energy spectrum(Sun et al., 2023) reported that the transmutation of both minor actinides and long-lived fission products is significantly enhanced by fast neutron spectra. Furthermore, international projects such as BREST-OD-300, MYRRHA, ALFRED and CLEAR have demonstrated the technological potential of lead-cooled fast reactors in reducing the long-term radiological burden of radioactive waste and in supporting sustainable fuel cycle management. (Liu et al., 2020; Sun et al., 2023; IAEA, 2022; Alemberti, 2020). However, most of the published studies have treated individual aspects such as core design, neutronic analysis, thermal-hydraulic performance, reactor safety or fuel reprocessing, and few comprehensive evaluations have been made to integrate the role of the fast neutron spectrum in minor actinide transmutation and long-lived waste reduction. Moreover, significant research gaps are still present with regard to issues of fuel reprocessing, minor actinide management and neutron spectrum optimization(Kiegiel et al., 2025; Zhang et al., 2025).

Thus, the aim of this systematic review is to synthesize and critically evaluate the literature on the role of the fast neutron spectrum in the transmutation of minor actinides and the reduction of long-lived radioactive waste in Lead-cooled Fast Reactors. In particular, it is aimed at: (i) evaluating the impact of the fast neutron spectrum on the transmutation of minor actinides and long-lived fission products; (ii) comparing the neutronic features and transmutation performances of LFRs described in the literature; (iii) identifying the main parameters influencing the transmutation efficiency, the fuel cycle performance and the radioactive waste minimization; (iv) identifying the current research gaps and the future perspectives for the development and optimization of the Generation IV lead-cooled fast reactors. By synthesizing current evidence and comparing previous findings, this review provides a scientific basis for future research on advanced reactor design, nuclear fuel cycle optimization, and sustainable radioactive waste management.

2. MATERIALS AND METHODS

2.1. Study Design

The present study was carried out as a systematic review based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. This review was designed to systematically find, assess, compare and synthesize the published evidence on the role of the fast neutron spectrum in the transmutation of minor actinides and the reduction of long-lived radioactive waste in Lead-cooled Fast Reactors (LFRs). The review followed a systematic process including literature searching, study selection, data extraction, qualitative synthesis of findings, and critical appraisal of available evidence.

2.2. Information Sources

A comprehensive search of literature was conducted using the following electronic scientific databases: Scopus, ScienceDirect, Google Scholar and International Atomic Energy Agency (IAEA). These databases were chosen because they include a large portion of the peer-reviewed literature pertaining to nuclear engineering, reactor physics, fuel cycle technologies and radioactive waste management.

2.3. Search Strategy

We conducted a literature search using combinations of predefined keywords and Boolean operators (AND, OR) to optimize the retrieval of relevant studies.

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The main search terms used were:

- Lead-cooled Fast Reactor (LFR)
- Fast Neutron Spectrum
- Fast Reactor
- Minor Actinides
- Nuclear Waste
- Partitioning and Transmutation (P&T)
- Transmutation
- Generation IV Reactor
- Closed Fuel Cycle

2.4 Typical search expressions included

(Lead-cooled Fast Reactor OR LFR) AND (Fast Neutron Spectrum) AND (Minor Actinides) AND (Transmutation)
Additional relevant publications were identified by screening the reference lists of the included articles.

2.5. Eligibility Criteria

Studies were selected according to predefined inclusion and exclusion criteria.
Inclusion criteria**:**

- Peer-reviewed journal articles.
- Articles published in English.
- Studies focusing on Lead-cooled Fast Reactors (LFRs), fast neutron spectra, minor actinides, radioactive waste reduction, or Partitioning and Transmutation (P&T).
- Experimental, computational, analytical, and review studies relevant to the research objectives.
- Publications from recognized scientific journals and international organizations.

Exclusion criteria:

- Conference abstracts, editorials, commentaries, and non-peer-reviewed publications.
- Duplicate records.
- Studies unrelated to fast reactors or radioactive waste transmutation.
- Publications lacking sufficient technical or scientific information.

2.6. Study Selection

The exported records were imported and screened in several stages: First, duplicate records were deleted. Thereafter, independent screening of titles and abstracts for relevance was performed. Articles in full text that fulfilled the inclusion criteria were then examined in detail for inclusion in the final review. The selection of studies was based on PRISMA 2020 and will be illustrated with the PRISMA flow diagram.

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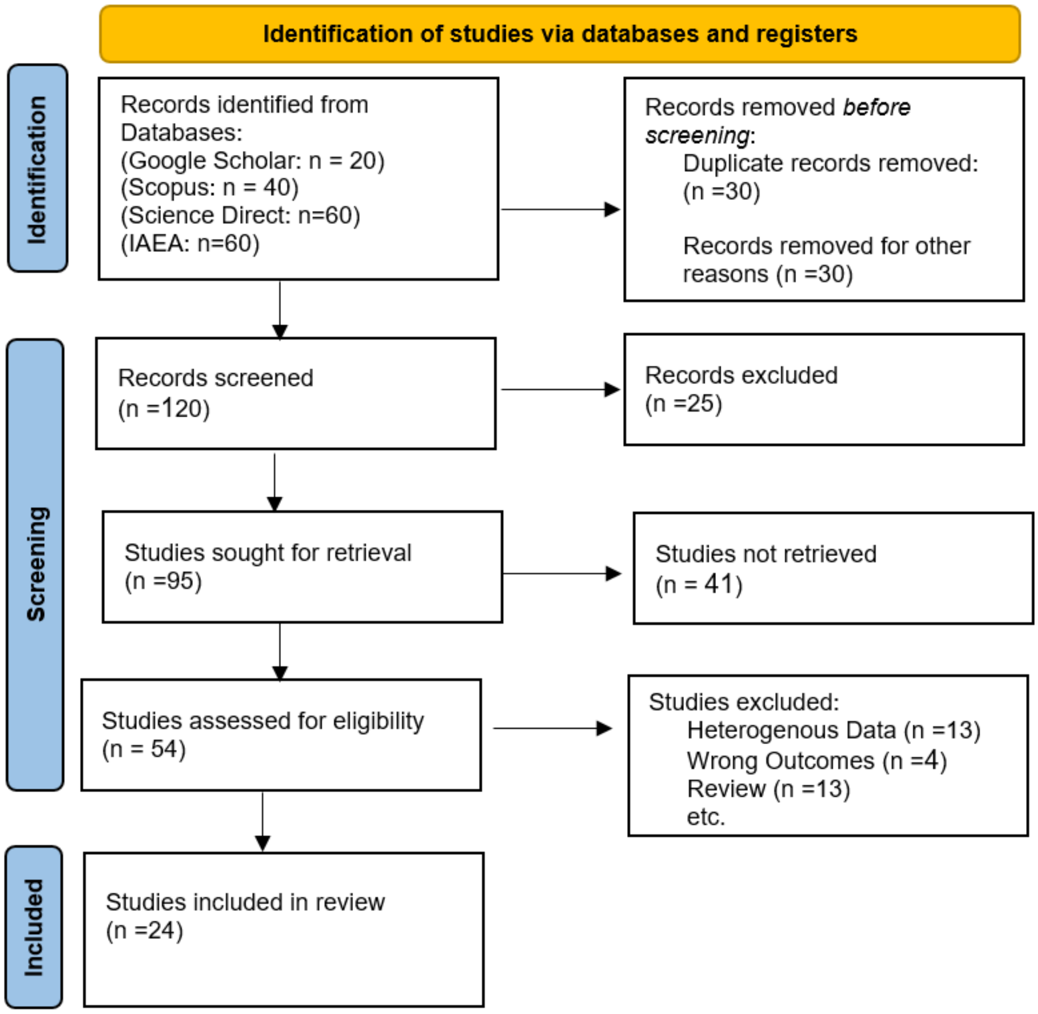

Figure 1. PRISMA 2020 flow diagram of the study selection process.

2.7. Data Extraction

Relevant information was systematically extracted from each included study using a standardized data extraction approach. The extracted information included:

- Author(s) and publication year
- Reactor type
- Fuel type
- Neutron spectrum characteristics
- Minor actinides investigated
- Transmutation performance
- Reactor neutronic characteristics
- Key findings and conclusions

2.8. Quality Assessment

The methodological quality and scientific relevance of the included studies were critically appraised concerning their research objectives, methodological rigor, consistency of reported results and relevance to the objectives of the present review. Particular

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emphasis was placed on studies published in reputable peer-reviewed journals and reports published by internationally recognized organizations such as the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (OECD/NEA).

2.9. Data Synthesis and Analysis

A narrative synthesis was used to qualitatively integrate and compare the findings of the included studies. The evidence was discussed with particular reference to the effect of the fast neutron spectrum on transmutation of minor actinides, reduction of long-lived radioactive waste, reactor neutronic performance and closed fuel cycle applications in Lead cooled Fast Reactors. Similarities, differences, current research trends and existing knowledge gaps were identified and critically discussed to provide a holistic understanding of the present state of research.

RESULTS

Transmutation of Minor Actinides (MAs) and Long-Lived Fission Products (LLFPs)

The simulation studies reviewed in this work were mostly performed using the OpenMC Monte Carlo code, and they show that the fast neutron spectrum in Lead-cooled Fast Reactors (LFRs) is very effective for the transmutation of minor actinides (MAs) and long-lived fission products (LLFPs) (Sun et al., 2023). The performance of the transmutation was evaluated by the Annual Transmutation Rate (TR) and the Support Ratio (SR). The TR is the percentage of a nuclide destroyed during irradiation in a year whereas the SR indicates if the amount transmuted is greater than the amount produced inside the reactor. If SR is larger than one, this indicates self-sustained transmutation.

The study results indicated that the proposed core configuration of Lead-cooled fast reactor (LFR) can achieve simultaneous transmutation of minor actinides (MAs) and long-lived fission products (LLFPs). In this design, five minor actinide nuclides, Np-237, Am-241, Am-243, Cm-244 and Cm-245 were loaded in the fuel assembly region and six LLFP nuclides, Se-79, Zr-93, Tc-99, Pd-107, I-129 and Cs-135 were loaded in dedicated LLFP assembly regions. The optimization results of the MA loading and LLFP composition indicated that the LFR operational characteristics and the support ratio (SR) could be reasonably balanced by optimizing these parameters. Moreover, the calculation of the neutronic parameters of the reactor such as the effective multiplication factor (k_{eef}) and the neutron flux distribution indicated that the proper amount of MA loading has a negligible effect on the neutronic performance of the reactor core. Analysis of the connection of the transmutation efficiency with the reactor operating time showed that the fast neutron spectrum in LFR provides an effective ability to reduce the inventory of minor actinides and long-lived fission products (Sun et al., 2023).

The study conducted by Sun et al., (2023) shows that the fast neutron spectrum in Lead-cooled Fast Reactors (LFRs) can be used for the simultaneous transmutation of Minor Actinides (MAs) and Long-Lived Fission Products (LLFPs). In this design the minor actinides are loaded into the fuel assemblies and the long lived fission products are placed in the reactor blanket region. This will allow the excess neutrons generated during the fission process to be utilized for converting these materials into shorter lived or stable isotopes(Sun et al., 2023).

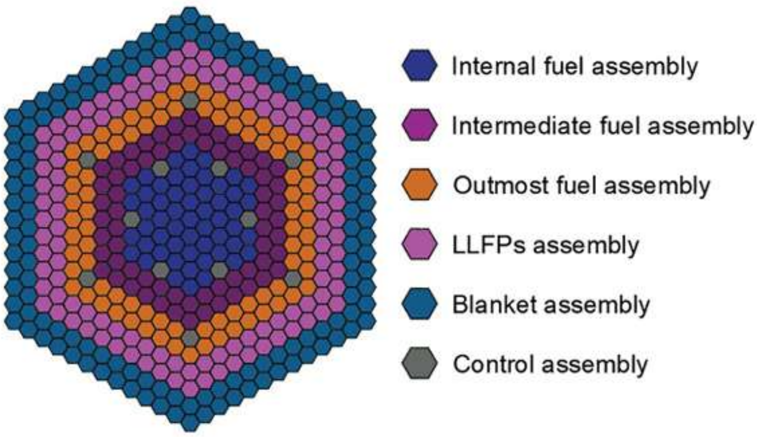

Figure 1. Schematic diagram of the LFR core.

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The studies considered show that the optimum condition for efficient transmutation is reached when the reactor core contains 1.5 wt% of minor actinides. Under these conditions, the maximum annual transmutation rate is obtained for Am-241 (15.18 %), followed by Am-243 (13.34 %) and Np-237 (13.07 %). Their support ratios are between 1.22 and 1.63, which confirms that the fast neutron spectrum can destroy these nuclides faster than they are produced.

The transmutation of the long-lived fission products in the radial blanket, namely Se-79, Tc-99, Pd-107 and I-129 are also successful and have support ratios greater than unity. However, some isotopes such as Cm-244 and Cm-245 have negative transmutation rates because they continue to accumulate during irradiation. However their total mass is still less than 5 % of the total MA stock, thus they have little influence on the global performance of the reactor.(Sun et al., 2023).

Table 1. Annual Transmutation Rates (TR) and Support Ratios (SR) for MAs and LLFPs in an LFR Core (Sun et al., **2023)**

Waste Nuclide	Annual TR (%)	Support Ratio (SR)
Np-237	13.07	1.22
Am-241	15.18	1.63
Am-243	13.34	1.27
Se-79	0.58	1.32
Tc-99	0.92	1.53
Pd-107	1.17	1.02
I-129	0.56	1.12

Reactor Neutronic Performance and Fuel Utilization

It follows from the studies considered that the addition of 1.5 wt% of minor actinides results in a decrease of the effective multiplication factor (k_{eff}) at the beginning. But the reactivity decrease during the reactor operation is much slower than in the case of conventional fuel cores. After approx. 1300 days of irradiation the $k_{eff}$of the MA-loaded core is similar to and then higher than that of the reference core(Sun et al. (2023).

This behavior is explained by the neutron absorption conversion of fertile isotopes such as Np-237 and Am-241 into fissile nuclides which partially offsets the fuel depletion. Moreover, the results of the studies reviewed show that the addition of minor actinides leads to a minor reduction (around 3.98%) of the peak neutron flux while the neutron energy spectrum remains almost unchanged. Results confirm that fast neutron nature of the reactor is preserved and the efficiency of fuel utilization is preserved (Sun et al., 2023; G. I. Toshinsky et al., 2020).

Comparison of Fast and Thermal Neutron Spectra

The net neutron consumption per fission, called D-factor, is also used to evaluate the effectiveness of the radioactive waste transmutation. The reviewed literature indicates that fast-spectrum reactors have negative D-factor values for transuranic isotopes, which means they are net neutron producers and have favorable conditions for fission. In contrast, thermal reactors like Light Water Reactors (LWRs) tend to have positive D-factor values, indicating that neutron capture is more prevalent than fission, resulting in higher production of heavier actinides.(OECD/NEA, 2002; Stanisz et al., 2015).

Table 2. Neutron Consumption per Fission (D-factor) in Fast and Thermal Reactors

Isotope	Fast Reactor (LFR/ADS)	Thermal Reactor (LWR)
Np-237	-0.59	1.12
Am-241	-0.62	1.12
Am-243	-0.60	0.82
Pu-239	-1.46	-0.67
Pu-240	-0.96	0.44

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Contribution of Fast Neutron Spectrum to Waste Reduction and Closed Fuel Cycle

The reviewed evidence shows that the fast neutron spectrum contributes significantly to reducing the long-term inventory of minor actinides and thus the radiotoxicity of the spent nuclear fuel. More than 95% of the total MA inventory is Np-237, Am-241 and Am-243, all of which have positive transmutation rates and support ratios > 1. This results in a large reduction in the quantity and long-term radiotoxicity of high-level radioactive waste.

In addition, the successful transmutation of long-lived fission products enables the development of a closed nuclear fuel cycle in which uranium, plutonium and selected minor actinides are recycled into new fuel assemblies, rather than being disposed of as waste. This process increases fuel utilization, decreases the amount of material requiring geological disposal, and improves the long-term sustainability of nuclear energy systems (Sun et al., 2023).

The analyzed studies show that the loading of minor actinides reduces the effective delayed neutron fraction (β_{eff}) by ~50% as compared to the conventional MOX-fueled fast reactors. Moreover, the Doppler feedback coefficients of lead-cooled reactors are of the order of $-0.3\ to\ -0.5\ pcm/K$ which are smaller in magnitude than those previously reported for sodium-cooled fast reactors(K. Zhang et al., 2023).

Regarding coolant activation, Lead-Bismuth Eutectic (LBE) generates significant quantities of Polonium-210, whereas pure lead produces approximately three orders of magnitude less, offering improved radiological performance (G. I. Toshinsky et al., 2020).

The literature reviewed also identifies MYRRHA and BREST-OD-300 as the main demonstration projects for advanced LFR technology. MYRRHA is a subcritical Accelerator-Driven System (ADS) with $k_{eff} \approx 0.95$ and a fast neutron flux of $10^{15}\ n/cm^2 \cdot s$, while BREST-OD-300 uses pure lead coolant and mixed nitride fuel for a closed fuel cycle and efficient transmutation of long-lived radioactive waste.

Role of the Fast Neutron Spectrum in Nuclear Waste Reduction

The studies reviewed all show that the fast neutron spectrum is important for minimizing long-lived radioactive waste in Lead-cooled Fast Reactors (LFRs). The fast neutrons increase the probability of fission in heavy actinides compared to thermal neutron spectra , enabling the transmutation of long-lived radionuclides to shorter-lived fission products (IAEA, 2022).

Nuclear Transmutation of Minor Actinides

The literature review has identified nuclear transmutation as the main mechanism for reducing long-lived radioactive waste in Generation IV reactor systems. The process uses neutrons to trigger nuclear reactions that convert radioactive isotopes to different isotopes. The minor actinides (Neptunium, Americium, and Curium, Np, Am and Cm) are more readily fissioned in fast neutron spectra than in thermal reactors and therefore, the destruction rate is increased.

An example of a fission reaction is:

$$^{241}_{95}Am + n \rightarrow Fission\ Products + 2{\sim}3n + Energy$$

Studies on the BREST-OD-300 and BR-1200 reactor concepts also show that strategies for a closed nuclear fuel cycle recycle uranium, plutonium and selected minor actinides into new fuel assemblies after reprocessing, with fission products and part of the curium inventory removed. (Balovnev et al., 2021).

According to the reviewed studies, minor actinides including Np, Am and Cm are effectively transmuted in the fast neutron spectrum of LFRs. These nuclides are neutron induced fissioned or capture reaction to decrease the inventory in the reactor core after fuel loading. The general reaction of transmutation is:

$$Minor\ Actinides\ +\ Fast\ Neutrons\ \rightarrow Fission\ Products\ +\ Energy$$

The literature reviewed also shows that keeping a fast neutron spectrum increases the chance of fission of minor actinides compared with thermal spectrum reactors. (IAEA, 2022). Reactor analyses further indicate that increasing americium content requires gradual adjustment of plutonium concentration in recycled fuel to maintain core reactivity (Balovnev et al., 2021).

Reduction of Long-Lived Radioactive Isotopes

The reviewed publications consistently report that isotopes such as Np-237, Pu-239, and Am-241 are efficiently transmuted under fast neutron irradiation. These reactions reduce the inventory of long-lived radionuclides while producing shorter-lived isotopes or fission products (*Generation IV International Forum (GIF). (2022). 2022 GIF Annual Report*, 2022).

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The simulation results for the BREST-OD-300 reactor showed that the fraction of Am-241 increased from about 0.3% to about 1.7% for the first 30 years of operation and then reached equilibrium. The BR-1200 reactor shows similar behaviour in the concentration of Am-241, which reaches a steady level of about 1.5% after almost 60 years.(Balovnev et al., 2021).

It has been demonstrated that the Lead-cooled Fast Reactors (LFRs) allow the multi-recycling of plutonium and minor actinides (MAs) through a closed nuclear fuel cycle, thus avoiding the build-up of long-lived radioactive waste with these nuclides. The repeated recycling of fuels gradually leads the fuel cycle to an equilibrium state. This results in a progressive reduction of the inventory of long-lived radioactive nuclides while allowing the reuse of fissile materials in the reactor system. (Stanisz et al., 2015).

Radiotoxicity and Final Waste Reduction

The reviewed studies report that the transmutation of minor actinides significantly decreases the long-term radiotoxicity of high-level radioactive waste because heavy actinides are the principal contributors to long-term radiological hazards (ECD/NEA, 2021).

The literature also indicates that closed fuel cycle strategies implemented in fast reactors increase the recycling of uranium and plutonium, thereby reducing the amount of waste requiring final geological disposal (World Nuclear Association, 2026; *Generation IV International Forum (GIF). (2022). 2022 GIF Annual Report*, 2022).

However, the reviewed evidence further shows that transmutation technologies do not completely eliminate the need for deep geological repositories because long-lived fission products remain in the waste stream and still require final disposal (Grambow, 2022).

The reviewed study shows that the loading of minor actinides (MAs) in the core of Lead-cooled Fast Reactor (LFR) with different loading schemes does not significantly affect the neutron flux distribution and the core power density, if appropriate loading fraction is used. The calculated power peaking factor was almost unchanged, indicating the MA transmutation can be performed without serious deterioration of the neutronic performance of the reactor. Furthermore, although the effective multiplication factor k_{eff} decreases slowly during the reactor operation, the MA-loaded core remains critical over the whole operating cycle and shows a slight extension of the fuel cycle. This behavior is due to the in situ production of new fissile isotopes, which partially compensate reactivity loss due to fuel depletion (Liu et al., 2020).

Changes in Isotopic Inventory and Reduction of Radioactive Waste

The simulation results also show that the irradiation of minor actinides in the LFR core leads to a significant decrease in the concentrations of Np-237, Am-241 and Am-243, while the concentrations of Cm-244 and Cm-245 increase due to successive neutron-capture reactions. Furthermore, a 750 MWth Lead-cooled Fast Reactor with about 1 wt% minor actinide can transmute the yearly production of minor actinides from about 1.5 conventional Pressurized Water Reactors (PWRs). Moreover, the spent fuel after MA transmutation contains about 85 wt% Pu isotopes and the rest is other transuranic isotopes including the valuable fissile isotope, Pu-238 which is produced during irradiation. These findings indicate that LFR technology can substantially reduce the inventory of long-lived minor actinides while simultaneously producing reusable fissile materials, thereby supporting the sustainability of the closed nuclear fuel cycle (Liu et al., 2020).

Moderator-Assisted Transmutation Performance

The study conducted by Rohan and Sahadath .(2023) demonstrates that the use of moderator coatings around fuel elements in a Lead-cooled Fast Reactor (LFR) can enhance the transmutation efficiency of Minor Actinides (MAs). In this study, a fuel assembly based on the ALFRED design with 5 wt. % of MAs homogeneously mixed into MOX fuel was investigated with different moderator materials. Simulation results showed that transmutation rates of the investigated actinides were improved with increasing moderator coating thickness. The best transmutation performance was found for ZrH 1. 6 among the moderators under evaluation. The annual transmutation rate for Np-237, Am-241 and Am-243 were found to be 13.57%, 12.60% and 9.26% with a coating thickness of 0.01 cm. However, the inventories of Cm-243, Cm-244 and Cm-245 increased during irradiation due to successive neutron-capture reactions of americium, uranium, and plutonium isotopes.(Rohan & Sahadath, 2023).

The results also showed that moderator coatings enhance the transmutation efficiency of Minor Actinides, and they influence the fuel cycle parameters. The increased moderator thickness decreased fuel burnup and fuel cycle length. $ZrH_{1.6}$ showed the greatest decrease of these parameters among the studied materials, while deuteride moderators showed smaller negative effects, but lower

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transmutation rates. Furthermore, the analysis of the infinite multiplication factor (k_∞), fuel temperature coefficient, neutron energy spectrum and relative pin-power distribution showed that the modification of the neutronic characteristics of the reactor core by the addition of moderator coatings does not deteriorate the capability of the LFR system for the transmutation of long-lived Minor Actinides (Rohan & Sahadath, 2023).

The results of Takeda, (2016) showed that the transmutation of minor actinides (MAs) in fast reactors can be evaluated using two main indicators: the difference between the amount of actinide nuclides before and after the burnup period, and the combined effect of direct fission and net plutonium production from the target nuclides. This technique was applied to study the behaviour of single isotopes like Np and Am under various irradiation conditions. The calculations for fast reactors with homogeneous MA loading in the core and heterogeneous loading in the blanket region indicated that the transmutation rate of these nuclides depends on neutron spectrum, neutron flux and irradiation period. The total amount of MA transmutation also increased with increasing burnup time. The role of fission in reducing these nuclide inventories became more important during longer irradiation period. (Takeda, 2016)

DISCUSSION

The results of this systematic review are that the fast neutron spectrum of Lead-cooled Fast Reactors (LFRs) is a very good medium for the transmutation of Minor Actinides (MAs) and Long-Lived Fission Products (LLFPs). The present review shows that isotopes like Np-237, Am-241 and Am-243 have high transmutation rates and SR values (Support Ratio) greater than 1 which means these nuclides are destroyed at a rate faster than their production rate. These findings are in agreement with the study of Sun et al., (2023), who reported annual transmutation rates of 13.07%, 15.18%, and 13.34% for Np-237, Am-241, and Am-243, respectively, together with SR values greater than one. Similar conclusions were reported by Takeda, (2016), who demonstrated that the transmutation efficiency of minor actinides in fast reactors strongly depends on the neutron spectrum, neutron flux, and irradiation time, and that longer irradiation periods increase the overall transmutation of MAs.

The present review also indicates that the fast neutron spectrum maintains favorable neutronic characteristics while supporting efficient waste transmutation. This observation is consistent with Liu et al., (2020), who found that loading approximately 1 wt.% MA into the reactor core causes only minor changes in neutron flux distribution and reactor power while maintaining core criticality throughout the operating cycle. Likewise, Sun et al., (2023) reported that an MA loading of around 1.5 wt.% provides a good compromise between transmutation efficiency and reactor performance without significantly degrading the neutron flux distribution or the effective multiplication factor (k_{eff}). These consistent results suggest that improved MA loading may lead to increased radioactive waste reduction without substantial disruption to reactor operation.

The reviewed studies further demonstrate that LFRs can simultaneously transmute both Minor Actinides and Long-Lived Fission Products through dedicated fuel assemblies and blanket regions. This finding agrees with Sun et al., (2023), who demonstrated that the proposed LFR core configuration has the capability to efficiently transmute both waste categories and the ability to accommodate a closed nuclear fuel cycle. The current review also confirms the clear advantages of fast-spectrum reactors when compared to thermal-spectrum reactors. Fast neutrons promote fission reactions as opposed to neutron capture, thus limiting the buildup of long-lived transuranic isotopes. These observations agree with the conclusions reported by OECD/NEA, (2002) and Stanisz et al.,(2015) regarding the negative D-factor of fast reactors.

Despite these advantages, the reviewed studies consistently identify several limitations. The present review found that Cm-244 and Cm-245 continue to accumulate during irradiation because of successive neutron-capture reactions. Similar results were reported by Rohan & Sahadath, (2023), who observed an increase in curium inventories despite improved transmutation of neptunium and americium. Furthermore K. Zhang et al., (2023)) showed that MA loading decreases the effective delayed neutron fraction (β_{eff}) and hence may cause the safety margins of the reactor to be reduced. The results show that LFR technology greatly enhances radioactive waste transmutation, but further optimization is required to control curium production and maintain reactor safety.

The consistency of the findings of the present review with previous studies is, in general, a confirmation of the fact that the Lead cooled Fast Reactors are among the most promising Generation IV technologies for the transmutation of long-lived radioactive waste. However further investigations are required to optimize the MA loading, improve the management of curium, improve moderator assisted transmutation techniques and combine neutronic, thermal-hydraulic and safety analyses in support of the practical deployment of advanced LFR systems.

CONCLUSION

The outcomes of this systematic review show that the fast neutron spectrum in the Lead-cooled Fast Reactors (LFRs) is a good and effective medium for the transmutation of Minor Actinides (MAs) and Long-Lived Fission Products (LLFPs). The results show that important minor actinides, such as Np-237, Am-241 and Am-243, have significant annual transmutation rates with Support Ratio (SR) values larger than one, i.e. these radionuclides can be destroyed faster than they are produced in the reactor system. The reviewed studies also show that an optimized minor actinide loading of about 1.5 wt% can improve transmutation performance while maintaining acceptable neutronic characteristics of the reactor core.

Furthermore, the comparison between fast and thermal neutron systems indicates that the LFRs offer better conditions for the fission of transuranic elements, thanks to their negative D-factor values, thus improving the reduction of long-lived radioactive waste and the development of a closed nuclear fuel cycle. However, the results also show some remaining challenges, such as the curium isotopes build-up and the reduction of the effective delayed neutron fraction when loading minor actinides. Therefore, future LFR development should be directed to the improvement of transmutation strategies and reactor safety features to facilitate more efficient and sustainable nuclear waste management.

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