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Bibliometric Mapping of Studies on Neutron Absorber Materials and Criticality Safety in Spent Nuclear Fuel Management

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ABSTRACT

Spent nuclear fuel storage systems must remove decay heat, maintain radiation shielding and confinement, and prevent nuclear criticality during interim storage, transportation, and disposal-oriented handling. Neutron absorber materials are central, maintaining subcritical margins in storage racks, casks, baskets, and transport packages. Although bibliometric studies examined nuclear fuel cycle technologies or spent nuclear fuel research, none comprehensively integrated spent nuclear fuel storage, neutron absorber materials, decay heat, and criticality safety, limiting systematic understanding of their research landscape and evolving relationships. This study maps Scopus-indexed research from 2000 to January 2026 on spent nuclear fuel storage, neutron absorber materials, and criticality safety. Scopus yielded 599 records on 27 January 2026; document-type and language screening retained 236 English-language journal articles. VOSviewer and Microsoft Excel analyzed annual publication trends, country and author productivity, journal distribution, keyword co-occurrence, thematic clusters, and temporal trends. Publications generally increased after 2014, peaking in 2021 and 2024. The United States, South Korea, and China led contributions; main venues included *Annals of Nuclear Energy*, *Nuclear Technology*, and *Nuclear Engineering and Design*. Three themes dominated: spent nuclear fuel storage technologies, neutron absorber and shielding materials, and computational analysis for nuclear criticality safety. Temporal trends shifted from reactor-related computational studies toward storage technologies and recent performance evaluation of advanced neutron absorber and shielding materials. This comprehensive bibliometric mapping reveals major themes, leading sources, productive authors, and emerging trends. Findings highlight the need to integrate material characterization, neutron testing, degradation assessment, and criticality modeling for long-term spent nuclear fuel storage safety and reliability.

Keywords: Bibliometric analysis, spent nuclear fuel, neutron absorber materials, criticality safety, dry storage.



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INTRODUCTION

The management of spent nuclear fuel (SNF) is a strategic issue in the nuclear fuel cycle because irradiated fuel remains radioactive, generates decay heat, and may create criticality concerns if it is not stored in a controlled configuration after removal from the reactor core. Safe storage therefore requires an integrated system capable of maintaining subcriticality, removing heat, providing radiation shielding and confinement, and preserving retrievability for inspection, transportation, reprocessing, or final disposal [1], [2]. As nuclear power programs continue to generate SNF while final repositories remain limited in many countries, interim storage has become an increasingly important technical and regulatory domain.

SNF storage is commonly implemented through wet storage pools and dry storage systems. Wet storage provides cooling and radiation shielding through water, whereas dry storage relies on passive heat removal, robust canister or cask structures, and engineered barriers for confinement and shielding [1], [3]. The transition from pool storage to dry storage and ultimately to disposal increases the need for long-term safety assessments that integrate thermal performance, structural integrity, corrosion behavior, aging management, radiation shielding, and nuclear criticality control.

Among these safety functions, neutron absorption is a key mechanism for criticality prevention. Neutron absorber materials are installed in storage racks, baskets, panels, transportation packages, and disposal-related canisters to maintain adequate subcritical margins under normal, off-normal, and accident conditions [2], [4]. Their performance depends not only on initial absorber content, but also on areal density, corrosion resistance, mechanical stability, irradiation history, manufacturing quality, and the long-term retention of neutron-absorbing elements such as boron.

Research on neutron absorber and shielding materials has developed beyond conventional design verification toward the development and qualification of borated stainless steel, boron-aluminum alloys, B₄C/Al composites, polymer-based composites, and advanced shielding materials for storage and transportation applications [5], [6]. In parallel, criticality safety studies increasingly incorporate burnup credit, fuel depletion,

decay heat, canister loading optimization, and uncertainty analysis, reflecting the complexity of modern spent fuel inventories and repository-oriented safety cases [7], [8].

The expansion and diversification of this literature make bibliometric analysis useful for identifying publication trends, influential countries, productive authors, major journals, collaboration networks, and emerging thematic directions. Science-mapping approaches provide a systematic way to classify a body of literature and visualize the intellectual structure of a research field [9], [10]. Previous studies have reviewed nuclear fuel cycle strategies, spent nuclear fuel management technologies, and global nuclear waste management, while recent bibliometric analyses have primarily focused on nuclear waste management at a broader level [11]. However, these studies did not integrate spent nuclear fuel storage, neutron absorber materials, decay heat, and criticality safety within a single bibliometric framework, leaving the relationships among these interconnected topics insufficiently characterized. However, the specific intersection between spent nuclear fuel storage, neutron absorber materials, and criticality safety has not been comprehensively mapped for the period from 2000 to January 2026.

Accordingly, this study conducts a bibliometric analysis of Scopus-indexed journal articles on SNF storage, neutron absorber materials, and criticality safety during 2000-January 2026. By combining publication trend analysis, country and author productivity, journal distribution, keyword co-occurrence, thematic clustering, and co-citation mapping, the article offers a comprehensive bibliometric overview of the field and identifies highlights emerging research themes and potential future research directions relevant to long-term storage safety, material qualification, and research related to criticality safety and neutron absorber materials.

METHODOLOGY

a. Literature search and selection

Bibliometric analysis was conducted using the Scopus database because it provides broad coverage of peer-reviewed literature in engineering, nuclear technology, materials science, and energy-related fields [9]. All bibliographic data used in this study

were retrieved from Scopus on 27 January 2026. Because the search was conducted in January, publications from 2026 were treated as partial-year data and interpreted cautiously in the trend analysis.

The literature search was conducted using the following query: (TITLE-ABS-KEY ("Spent fuel" OR "Spent fuels" OR "spent nuclear fuel" OR "spent nuclear fuels" OR "nuclear fuel" OR "nuclear fuels" OR "spent fuel element" OR "spent fuel elements" OR "spent fuel assembly" OR "spent fuel assemblies")) AND (TITLE-ABS-KEY ("Storage" OR "spent fuel storage" OR "wet storage" OR "dry storage" OR "wet spent fuel storage" OR "dry spent fuel storage" OR "dry cask")) AND (TITLE-ABS-KEY ("neutron absorber material" OR "neutron absorber materials" OR "neutron shielding" OR "neutron shielding material" OR "neutron absorber" OR "neutron absorbers" OR "criticality" OR "criticality control" OR "subcriticality"))).

The search was limited to English-language journal articles published from 2000 to January 2026. The initial search identified 599 documents. After screening by document type, 282 journal articles remained; after applying the language filter, 236 documents were retained for bibliometric visualization and analysis. The search strategy was designed using TITLE-ABS-KEY fields to retrieve publications specifically related to spent nuclear fuel storage, neutron absorber materials, neutron shielding, and criticality safety. In addition, review-related publications, including bibliometric studies, scientometric studies, systematic reviews, scoping reviews, umbrella reviews, meta-analyses, and other secondary literature, were excluded through the search query. The titles and abstracts of the retrieved journal articles were subsequently checked to confirm their relevance to the scope of this study. No additional records were excluded at this stage because all 236 articles met the predefined inclusion criteria. The stepwise selection process is summarized in Figure 1.

b. Bibliometric analysis and thematic classification

Bibliometric assessment and visualization were performed using VOSviewer version 1.6.19 and Microsoft Excel 2021. VOSviewer was used to construct and

visualize networks based on co-authorship, citation relationships, and keyword co-occurrence; the similarity-based mapping approach used in VOSviewer is widely applied in bibliometric network visualization [12]. Before keyword mapping, synonymous terms were merged to improve consistency, and a LinLog/modularity-based layout was applied to clarify cluster separation. The VOSviewer analyses were performed using the full counting method. Country co-authorship analysis was conducted with a minimum threshold of one document per country, resulting in 46 countries included in the network. Source citation analysis used a minimum threshold of one document per journal, retaining 68 journals, while author citation analysis used a minimum threshold of three documents per author, retaining 58 authors after excluding documents with more than 25 authors. Keyword co-occurrence and overlay analyses were based on author keywords with a minimum occurrence threshold of four, resulting in 37 keywords. The default clustering resolution (1.0) was applied with the "merge small clusters" option enabled. The attraction parameter was set to 3 for all analyses, while the repulsion parameter was set to -6 for the country collaboration network and -1 for the citation and keyword networks.

Thematic clusters were first generated through author keyword co-occurrence analysis using VOSviewer, which automatically identified three keyword clusters (Clusters 1–3) based on keyword relationships. The resulting clusters were then interpreted based on the dominant author's keywords to identify the main research themes. The annual publication trends presented in Figure 2 are then compiled based on thematic clusters derived from the results of the VOSviewer analysis. The three thematic clusters identified include: (1) *spent nuclear fuel*, (2) storage systems, including *wet storage* and *dry storage*, and (3) neutron absorbing materials and critical safety, which include neutron absorbing materials, neutron *shielding*, *criticality*, and sub-critical (*subcriticality*). This analysis was limited to English-language journal articles indexed in Scopus; therefore, conference papers, technical reports, patents, and non-English publications are not included.

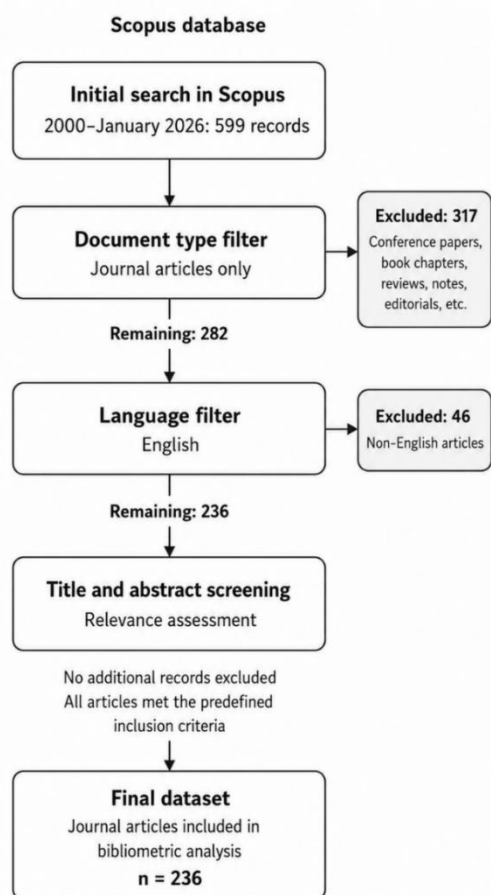


Figure 1. Flowchart of literature search and article selection based on the Scopus database

RESULTS AND DISCUSSION

a. Publication trend by year

Figure 2 shows the number of annual publications and their thematic distribution. A total of 236 publications were successfully identified during the period 2000 to January 2026. The number of annual scientific publications shows a pattern that fluctuates throughout the research period. The average number of annual publications increased from about 5 articles per year in the period 2000–2013 to about 13.5 articles per year in the period 2014–2025, which shows an increase in research activities despite fluctuations in the number of publications from year to year. After an increase in 2014, publication activity is relatively stable, generally ranging from 7 to 17 articles per year, with a peak of 17 articles in 2021 and 2024. Despite temporary declines in some years, particularly in 2016 and 2022, the level of publication after 2014 remained higher

than in the previous period, indicating continued research interest in waste nuclear fuel storage, neutron-absorbing materials, and critical safety. The 2026 data is partial because the literature search was conducted on January 27, 2026; therefore, the data only represents publications that have been indexed up to the search date and cannot be directly compared to the number of publications in the completed years.

At the thematic-cluster level, Figure 2 indicates differentiated development among the three research themes. Cluster 1 forms the dominant backbone of the literature and represents studies on spent nuclear fuel storage systems, particularly spent nuclear fuel, storage, and dry storage. Cluster 2 becomes increasingly prominent in the later period and focuses on neutron absorber materials and shielding technologies, including Al–B₄C, gadolinium, SS304–B₄C, SS316L–Gd, polymer composites, and related material performance. Cluster 3 represents computational analysis and safety assessment, encompassing nuclear criticality safety, burn-up, wet storage, Monte Carlo code, validation, uncertainty, PWR, BWR, SCALE, and depletion calculation. Collectively, these trends indicate a gradual expansion of research from storage technologies toward the integration of advanced neutron absorber materials and computational safety assessment for long-term spent nuclear fuel management. This transition reflects the growing need to integrate storage technologies with advanced neutron absorber materials and computational methods to ensure long-term nuclear criticality safety.

b. Research collaboration across countries/regions

Table 1 presents the top 10 countries/regions ranked by publication output in spent nuclear fuel safety management studies. The country-level analysis is presented according to the number of publications (documents), ranked from the highest to the lowest, while citation-based indicators, including total citations and citations per document, are discussed to indicate the research impact of each country. The analysis shows that research on spent nuclear fuel storage and neutron absorber materials is concentrated in a limited number of countries with active nuclear technology

programs. The United States ranked first with 59 documents and 728 citations, indicating both high research productivity and citation impact. South Korea ranked second with 40 documents and 492 citations, reflecting sustained national attention to spent fuel pool management, dry storage, and criticality safety. China ranked third with 28 documents and 554 citations, followed by Japan with 20 documents and 192 citations. Switzerland ranked fifth with 13 documents and 133 citations, while Turkey, France, the Czech Republic, Slovenia, India, Taiwan, Spain, Egypt and Iran each contributed between five and seven publications. Although Turkey ranked below the top five countries in terms of publication output, it recorded the highest citations per document, among the listed countries, indicating a relatively high research impact despite its lower publication volume. Overall, the publication distribution indicates that research in this field is dominated by countries with well-established nuclear power programs and long-term spent nuclear fuel management strategies.

The collaboration network shown in Figure 3 indicates that international collaboration is organized into several regional clusters rather than being evenly distributed across all countries. The United States occupies the most central position in the network and has the largest node, indicating

its prominent role in international collaboration. This finding is consistent with its leading publication output and citation impact (Table 1), reflecting the country's well-established research capacity and mature regulatory framework for spent fuel storage [2]. It is directly connected with Japan, the Netherlands, Canada, Armenia, and Turkey. China also demonstrates international collaboration through links with Pakistan, Japan, and Spain, whereas South Korea, despite ranking second in publication output, does not show international collaboration links in the present dataset. European countries form a dense collaboration network, with Switzerland and France each having 13 collaboration links and the Czech Republic having 14 links, primarily with other European countries. Turkey also maintains international collaborations through links with Jordan, India, Saudi Arabia, and the United States. Several other European countries also form closely connected collaboration clusters. This pattern suggests that research collaboration tends to develop among countries with established nuclear energy programs and well-developed research infrastructures. Therefore, international collaboration continues to play an important role in advancing research on spent nuclear fuel storage, neutron absorber materials, and criticality safety.

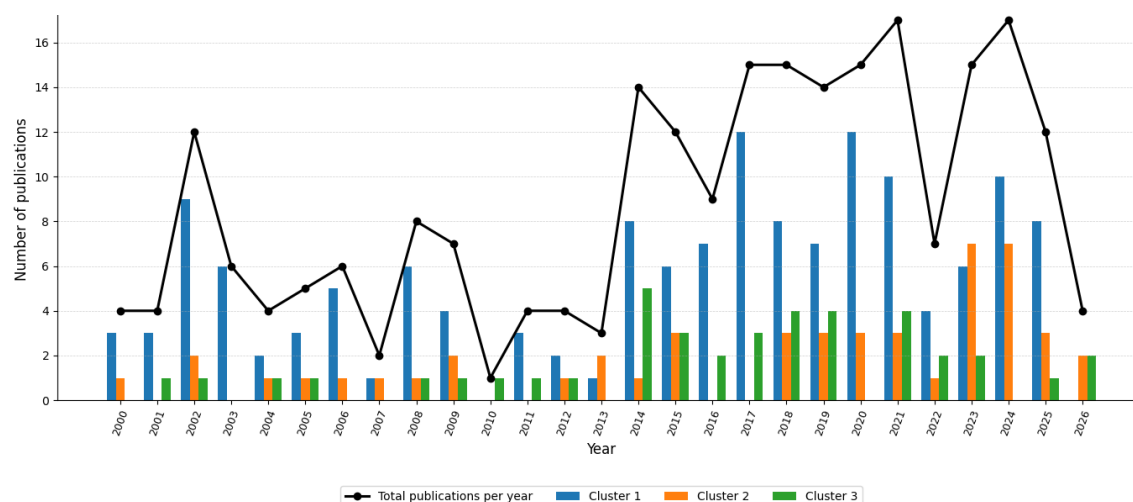


Figure 2. Annual publication output on spent nuclear fuel storage, neutron absorber materials, and criticality safety during 2000-January 2026

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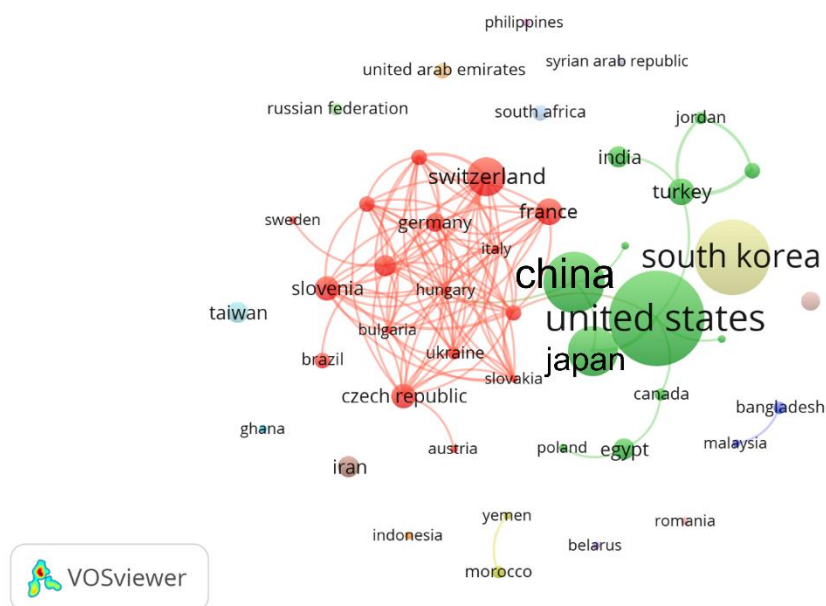


Figure 3. International collaboration network of countries/regions contributing to spent nuclear fuel storage and neutron absorber material studies.

Table 1. Top 10 countries/regions by publication output in spent nuclear fuel safety management studies.

No.	Country	Documents	Citations
1	United States	59	728
2	South Korea	40	492
3	China	28	554
4	Japan	20	192
5	Switzerland	13	133
6	Turkey	7	157
7	France	7	72
8	Czech Republic	6	70
9	Slovenia	6	43
10	India	5	87
11	Taiwan	5	33
12	Spain	5	32
13	Egypt	5	17
14	Iran	5	12

c. Leading journals in this field

Figure 4 illustrates the citation network of journals publishing research on spent nuclear fuel storage, neutron absorber materials, and criticality safety, while Table 2 summarizes the publication and citation performance of the ten most productive journals. The journals in Table 2 are ranked according to the number of published documents, from the highest to the lowest, whereas citation-based indicators, including total citations and citations per article, are presented to reflect the research impact of each journal. As shown in Figure 4, Annals of

Nuclear Energy occupies the largest and most prominent node in the citation network, indicating its dominant contribution and important position within this research field. Nuclear Engineering and Design, Nuclear Technology, and Nuclear Engineering and Technology also appear as prominent nodes, suggesting that these journals represent major publication venues for studies related to spent nuclear fuel storage, criticality safety, neutron shielding, and storage system analysis. Table 2 shows that Annals of Nuclear Energy published the largest number of articles (36 documents), followed by Nuclear Technology

(24 documents), Nuclear Engineering and Design (21 documents), Nuclear Engineering and Technology (16 documents), and Nuclear Science and Engineering (12 documents). These journals serve as the primary publication outlets for studies on criticality safety analysis, dry cask storage, spent fuel pool management, radiation shielding, and computational assessment of storage systems.

When citation impact is considered, a different pattern emerges. Although Journal of Nuclear Materials published only eight articles, it accumulated 258 citations and achieved the highest citations per article (32.2) among the listed journals, indicating that material-related studies on neutron

absorber degradation, corrosion, microstructural evolution, and long-term performance have received substantial scholarly attention despite their relatively lower publication output. Likewise, Progress in Nuclear Energy also demonstrates a relatively high citation impact (13.8 citations per article). Overall, the journal citation network demonstrates that research on spent nuclear fuel storage is inherently interdisciplinary, involving journals specializing in reactor physics, nuclear engineering, materials science, radiation protection, and nuclear safety assessment, reflecting the multidisciplinary nature of long-term spent nuclear fuel management [1], [13].

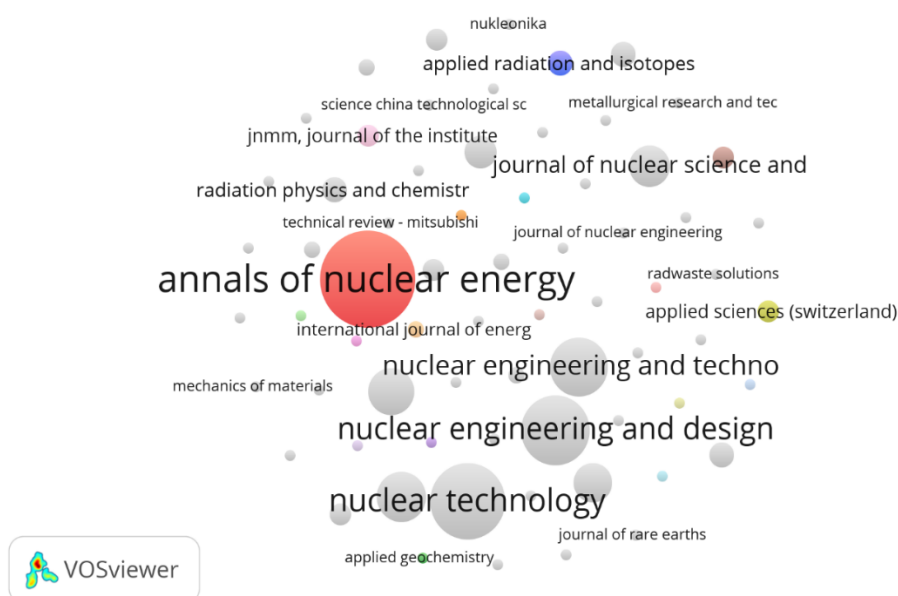


Figure 4. Journal-level distribution of publications in spent nuclear fuel safety management studies.

Table 2. Top 10 journals publishing research on spent nuclear fuel safety management

No.	Journal	Documents	Citations	Citations/article	H-index
1	Annals of Nuclear Energy	36	319	8.9	93
2	Nuclear Technology	24	201	8.4	69
3	Nuclear Engineering and Design	21	237	11.3	136
4	Nuclear Engineering and Technology	16	115	7.2	75
5	Nuclear Science and Engineering	12	84	7.0	69
6	Kernteknik	11	27	2.5	32
7	Journal of Nuclear Science and Technology	9	36	4.0	78
8	Journal of Nuclear Materials	8	258	32.2	182
9	Progress in Nuclear Energy	6	83	13.8	98
10	Applied Radiation and Isotopes	4	20	5.0	100

d. Thematics clusters and temporal evolution of research keywords

The keyword co-occurrence network (Figure 5) reveals three major thematic clusters that represent the principal research directions in spent nuclear fuel storage. The central cluster is dominated by spent nuclear fuel, storage, and dry storage, indicating that the primary focus of current research is the safe management of irradiated nuclear fuel under various storage configurations. As the largest and most central keyword, spent nuclear fuel serves as the main research hub linking studies on storage technologies, material development, and safety assessment. The central position of these keywords indicates that storage-related research forms the foundation of the field and provides connections to both material development and computational safety analysis. The prominence of dry storage reflects its increasing adoption as the preferred interim storage strategy because of its passive cooling capability, operational flexibility, and suitability for long-term storage applications. Consequently, research within this cluster primarily addresses storage system design, thermal management, shielding performance, structural integrity, and operational safety of dry storage facilities [14].

The second cluster focuses on neutron absorber materials and shielding technologies. Frequently co-occurring keywords include Al-B₄C, gadolinium, SS304-B₄C, SS316L-Gd, polymer composites, shielding neutron, shielding gamma, neutron transmission, mechanical properties, thermal conductivity, and corrosion. The coexistence of these keywords demonstrates that recent research has increasingly integrated material development with performance evaluation to ensure the long-term reliability of neutron absorber systems. Borated stainless steels, aluminum-based composites reinforced with boron carbide, gadolinium-containing alloys, and polymer composites have attracted considerable attention because they combine effective neutron attenuation with satisfactory mechanical strength, thermal stability, and corrosion resistance. These properties are essential for maintaining subcritical conditions throughout extended storage periods, particularly because neutron absorber components are generally inaccessible for replacement after installation [6], [15].

The third cluster is associated with computational analysis and safety assessment, including nuclear criticality safety, burn-up, wet storage, Monte Carlo code, validation, uncertainty, PWR, BWR, SCALE, and depletion calculation. These keywords indicate that computational analysis plays a fundamental role in supporting the design, licensing, and safety evaluation of spent fuel storage systems. Nuclear criticality safety represents a major research focus within this cluster, while Monte Carlo code, together with the SCALE code system, is widely applied to perform neutron transport and criticality calculations for spent fuel storage and transportation systems. Burn-up and depletion calculations are widely employed to estimate isotopic inventories and fuel reactivity, while validation and uncertainty analyses improve the reliability of computational safety assessments. The presence of wet storage reflects the continued importance of computational safety assessment for spent fuel pool management and storage operations. Overall, the keyword co-occurrence network demonstrates that research on spent nuclear fuel storage is highly interdisciplinary, with the central keywords spent nuclear fuel, storage, and dry storage connecting studies on storage technologies, neutron absorber materials, and computational safety analysis. This interconnected structure reflects the integration of engineering design, material development, and numerical analysis required to ensure the long-term safety and reliability of spent nuclear fuel management.

e. Keyword co-occurrence and temporal trends

The temporal overlay visualization (Figure 6) illustrates the evolution of research topics in spent nuclear fuel storage based on the average publication year of the associated keywords. Earlier studies (blue colours) primarily focused on uranium, LWR, and ORIGEN, indicating that the initial stage of research emphasized reactor-related analyses, fuel inventory calculations, and computational approaches for evaluating spent nuclear fuel characteristics. These topics provided the scientific basis for understanding fuel behaviour and supporting the development of storage safety analyses.

During the intermediate period (green colours), research became increasingly

centered on spent nuclear fuel, storage, dry storage, wet storage, burn-up, transport cask, polymer composites, dual purpose cask, neutron absorber materials, Al-B₄C, and gadolinium. The emergence of these keywords indicates that research expanded beyond computational analysis toward the development of storage technologies and neutron absorber materials for spent fuel management. This period reflects growing interest in integrating storage system design with radiation shielding and neutron absorption performance to enhance the safety and reliability of long-term spent nuclear fuel storage.

More recent studies (yellow colours) increasingly emphasize shielding gamma, shielding neutron, mechanical properties, thermal conductivity, and neutron transmission. The appearance of these keywords suggests that current research is shifting from the development of neutron

absorber materials toward improving their functional performance. In particular, recent studies place greater emphasis on optimizing radiation shielding effectiveness while simultaneously evaluating mechanical behaviour, heat transfer characteristics, and neutron attenuation performance to ensure the long-term reliability of advanced shielding materials under storage conditions.

Overall, the overlay visualization demonstrates a clear evolution of research from reactor analysis and computational modelling, through storage technologies and neutron absorber material development, toward performance-oriented evaluation of advanced shielding materials. This progression reflects the multidisciplinary nature of spent nuclear fuel storage research, in which computational analysis, engineering design, and material performance are increasingly integrated to support the long-term safety of spent nuclear fuel management.

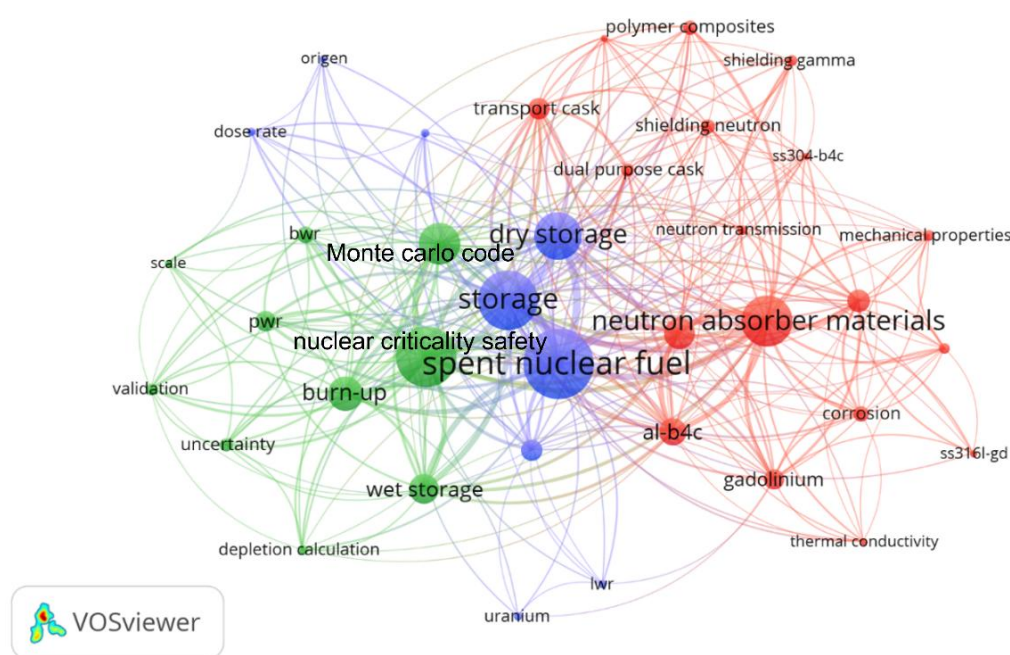


Figure 5. Keyword co-occurrence network of studies on spent nuclear fuel storage, criticality safety, and neutron absorber materials.

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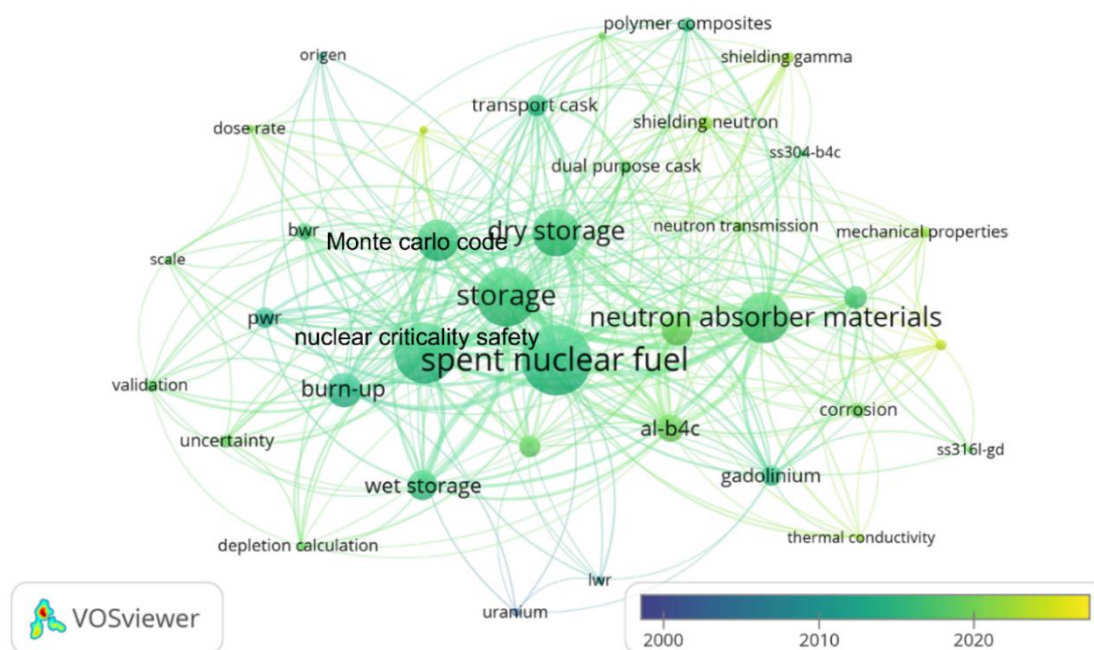


Figure 6. Temporal overlay map of keyword co-occurrence showing the evolution of major research topics.

f. Author productivity and citation analysis

Figure 7 presents the distribution of the most productive authors in spent nuclear fuel storage research, while Table 3 summarizes the publication output and citation performance of the ten leading authors. The authors listed in Table 3 are ranked according to the number of published documents, whereas citation counts are included to provide an indication of their scientific impact. As shown in Table 3, Hakim Ferroukhi and Alexander Vasiliev are the most productive authors, each publishing nine documents and receiving 92 citations. They are followed by John C. Wagner and Dimitri A. Rochman, each with seven publications, indicating their consistent contributions to this research field.

Figure 7 shows the relative distribution of productive authors within the bibliometric map. The larger nodes associated with Hakim Ferroukhi, Alexander Vasiliev, Dimitri A. Rochman, and John C. Wagner indicate their higher publication output compared with other authors in the dataset. However, citation impact does not always correspond directly to publication productivity. For example, although Marco Del Pecchia published five articles, he accumulated 61 citations, indicating a relatively high research impact compared with several authors having similar

publication output. Conversely, several productive authors, including Anthony Baratta, John W. Bartlett, Robert Brodsky, and Tom A. Hendrickson, have comparatively lower citation counts, suggesting that publication productivity and citation impact may differ substantially across authors.

Overall, the combined interpretation of Figure 7 and Table 3 indicates that spent nuclear fuel storage research is supported by multiple productive contributors rather than being dominated by a single author. While publication output identifies the leading contributors to the field, citation counts provide complementary information regarding the scholarly influence of their research.

The crystallite size estimated from the XRD results by the Scherrer equation is summarized in Table 2. The W film deposited at 4 kV shows one dominant W (110) peak at $2\theta \approx 40^\circ$ with no detectable (200) and (211) reflections. This reflects on a strong preferred orientation and limited crystal growth at the low deposition voltage. The crystallite size is about 8.98 nm, indicating the formation of nano crystalline structure. This suggests that the energy of the deposition is not sufficient to enhance the adatom mobility to favor the atomic diffusion and the formation of a fully developed BCC structure, typical of low energy thin film growth conditions [13].

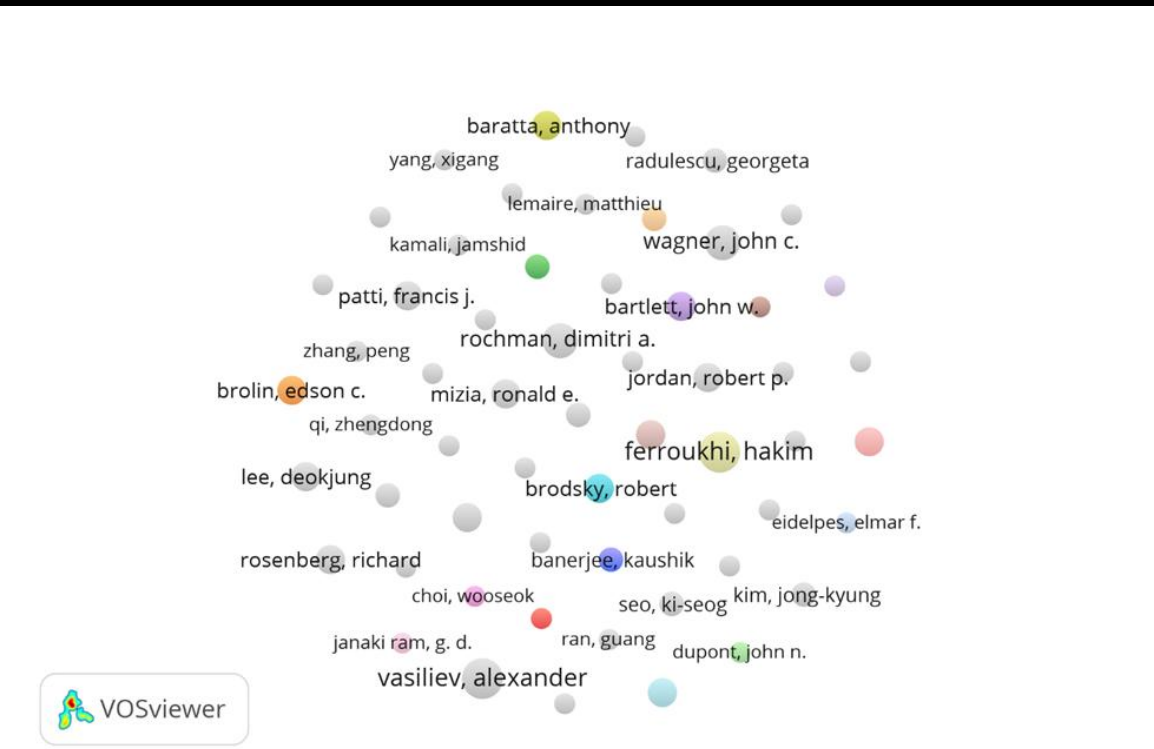


Figure 7. VOSviewer visualization of productive authors in spent nuclear fuel storage research

Table 3. Top 10 authors by publication output in spent nuclear fuel safety management studies

No.	Author	Documents	Citations
1	Ferroukhi Hakim	9	92
2	Vasiliev Alexander	9	92
3	Wagner John C.	7	68
4	Rochman Dimitri A.	7	64
5	Del Pecchia Marco	5	61
6	Baratta Anthony	5	0
7	Bartlett John W.	5	0
8	Brodsky Robert	5	0
9	Brolin Edson C.	5	0
10	Hendrickson Tom A.	5	0

g. Trends in neutron absorber materials, fabrication methods and testing

Based on the keyword co-occurrence and overlay analyses (Figures 5 and 6), neutron absorber materials have emerged as one of the major research themes in spent nuclear fuel storage. Recent literature shows a shift from conventional neutron absorbers toward multifunctional materials that can also serve as structural or shielding components resistant to long-term storage environments [16], [17], [18], [19]. The materials most frequently appearing in this discussion include borated stainless steel, boron-aluminium alloys, Al-B₄C metal matrix composites, B₄C-Al6061 composites, B₄C+Al₂O₃/Al-based hybrid systems, and polymer or concrete

shielding composites containing neutron-absorbing fillers [4], [5], [6], [20], [21], [22]. Functionally, B₄C remains the dominant filler or compound because the ¹⁰B isotope has a high thermal neutron absorption cross section, while aluminium matrices are selected for low density, good thermal conductivity, and formability [23]. Recent studies also pay greater attention to filler distribution, particle size, volume fraction, interfacial reactions, porosity, and the formation of interfacial compounds such as Al₄C₃ or complex borides because these factors affect boron areal density homogeneity, mechanical strength, corrosion resistance, and storage stability [20], [21].

Consistent with the material-related keywords identified in the bibliometric

analysis, an important development lies in balancing neutron absorption capability with mechanical integrity. Borated stainless steel offers structural stability and corrosion resistance, but increasing boron content can cause boride segregation and reduced ductility. B-Al alloys and Al-B₄C composites are lighter and suitable for dry cask baskets or panels, but they are sensitive to B₄C agglomeration, pore formation, and low wettability between ceramic B₄C and molten aluminum [20], [24]. Hybrid research has introduced additional fillers such as Al₂O₃, carbon fibers, or other neutron-absorbing oxides or elements to improve strength, microstructural stability, or shielding performance [25]. These hybrid designs show that optimization is no longer focused only on total boron content, but also on microstructural architecture, interfacial bonding, and consistency of filler distribution across the plate thickness [21], [22].

The overlay visualization further indicates that recent research has increasingly emphasized material performance and processing technologies. In terms of fabrication methods, the trend has shifted from conventional methods toward processes that can better control microstructure. Stir casting and melt-based casting are attractive because they are scalable, but they often face problems such as particle clustering, porosity, and low wettability between B₄C and aluminum [20], [26]. Powder metallurgy, including ball milling, compaction, sintering, hot extrusion, and hot rolling, is widely used because it can produce a more homogeneous B₄C distribution and improve particle-matrix bonding [24]. In addition, hot rolling, hot forging, extrusion, hot isostatic pressing, and friction stir additive processing have emerged as advanced approaches to reduce porosity, improve densification, control lamellar structures, and enhance strength-ductility combinations [21], [22]. Thus, neutron absorber fabrication trends are moving from merely producing absorber plates toward process control that maintains filler homogeneity, dimensional stability, and mechanical properties over long service life [27].

The increasing occurrence of keywords related to shielding performance and material properties also indicates that material qualification has become an important aspect of current research. Testing trends for neutron absorbers have also evolved from initial

compositional verification toward more comprehensive qualification schemes. ASTM C1671 emphasizes qualification and acceptance testing for boron-based neutron absorber materials, including the need to connect isotopic testing, areal density, and neutron attenuation testing with the criticality function in storage and transportation systems [4]. At the material level, neutron radiography and thermal neutron attenuation testing are used to examine the homogeneity of B₄C or ¹⁰B distribution, while mechanical testing (e.g., hardness, tensile, and bending tests), microstructural characterization using SEM/TEM, phase characterization using XRD, corrosion testing, accelerated aging testing, and post-irradiation evaluation are needed to ensure that neutron absorber performance not only meets initial values but also remains stable during operation [23]. Future research should therefore combine neutron test results, microstructural characterization, environmental degradation data, and criticality models so that material acceptance criteria can be linked directly to subcriticality margins and long-term storage safety cases [28], [29], [30].

h. Limitation

This study has several limitations that should be considered when interpreting the findings. First, the bibliometric analysis was conducted exclusively using the Scopus database. Although Scopus provides broad coverage of peer-reviewed literature in engineering, materials science, and nuclear technology, relevant publications indexed only in other databases may not have been captured. Second, the analysis was restricted to English-language journal articles published between 2000 and January 2026. Consequently, non-English publications and publications released after the search date were not included. Third, conference papers, technical reports, patents, review articles, and other secondary literature were excluded to maintain a consistent dataset of original research articles. While these document types may contain valuable technical developments and practical guidance, particularly in the field of nuclear engineering and spent nuclear fuel management, they were beyond the scope of the present bibliometric analysis. Therefore, future studies could provide a more comprehensive understanding of the research landscape by integrating multiple bibliographic

databases, including additional document types, and considering publications in multiple languages.

CONCLUSIONS

This study presents a bibliometric analysis of 236 Scopus-indexed journal articles published between 2000 and January 2026 on spent nuclear fuel storage, neutron absorber materials, and criticality safety. The results demonstrate a sustained increase in research activity, particularly after 2014, reflecting the growing importance of ensuring the long-term safety of spent nuclear fuel storage systems. The United States, South Korea, and China emerged as the leading contributors to this research area, while *Annals of Nuclear Energy*, *Nuclear Technology*, and *Nuclear Engineering and Design* were identified as the principal publication venues, highlighting their central role in disseminating research on spent nuclear fuel management and criticality safety.

The keyword co-occurrence analysis identified three major research themes comprising spent nuclear fuel storage technologies, neutron absorber and shielding materials, and computational analysis for nuclear criticality safety and storage safety assessment. Furthermore, the overlay visualization revealed a clear evolution of research topics from reactor-related computational analyses toward storage technologies and, more recently, the performance evaluation of advanced neutron absorber materials. The increasing prominence of keywords such as shielding neutron, shielding gamma, mechanical properties, thermal conductivity, and neutron transmission indicates that current research increasingly emphasizes the functional performance and long-term reliability of neutron absorber materials in addition to their neutron attenuation capability.

Based on these bibliometric findings, future research should strengthen the integration of neutron absorber material development with comprehensive performance evaluation, including neutron attenuation, mechanical behavior, thermal performance, corrosion resistance, and long-term durability. This recommendation is supported by the overlay analysis, which demonstrates a recent shift toward performance-oriented material research. Furthermore, the close relationship between

storage technologies, neutron absorber materials, and computational methods for nuclear criticality safety identified in the keyword co-occurrence network suggests that future studies should integrate material characterization, neutron testing, degradation assessment, criticality modeling, and advanced computational tools to support more reliable long-term safety assessments for spent nuclear fuel storage and transportation systems.

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DECLARATION OF AI-USAGE

During the preparation of this work the authors used ChatGPT to check language clarity and grammar. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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