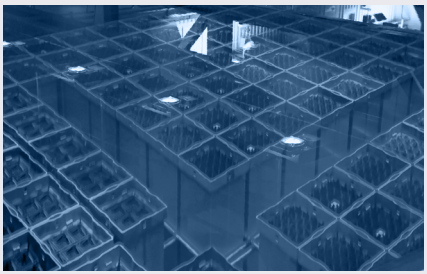
Nuclear Science
2025



Summary of the NEA Assessment on Spent Nuclear Fuel Decay Heat for Light Water Reactors

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Summary of the NEA Assessment on Spent Nuclear Fuel Decay Heat for Light Water Reactors

A Report by Subgroup 12 of the NEA Working Party on Nuclear Criticality Safety

NEA No. 7733

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Cover photos: Spent nuclear fuel pool (IAEA/CC BY 2.0); Central Interim Storage Facility for Spent Nuclear Fuel, Sweden (SKB).

Foreword

The Working Party on Nuclear Criticality Safety (WPNCS) was established under the Nuclear Energy Agency (NEA) Nuclear Science Committee (NSC) to investigate challenges and opportunities in the broad field of nuclear criticality safety. Within the WPNCS, Subgroup (SG) 12 was launched in 2022 to answer several questions related to spent nuclear fuel (SNF) decay heat, from both an experimental and a theoretical aspect. The main recommendation from Subgroup 12 concerns the need for new measurements of SNF decay heat, based on a calorimetric approach. The current experimental database contains measurements for SNF assemblies with lower initial enrichment and burn-up values compared to today's use of fuel assembly characteristics and concerns standard pressurised water reactor (PWR) UO_2 fuel.

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The member countries of the Nuclear Energy Agency (NEA), including the Nuclear Science Committee (NSC) and its Working Party on Nuclear Criticality Safety (WPNCS), acknowledge the significant contributions of the experts who participated in the subgroup and co-authored this report. Additional thanks are extended to Julie-Fiona Martin, Shahab Dabiran and Kelsey Amundson (NEA) in support of the preparation of this summary.

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List of abbreviations and acronyms

ATF	Accident-tolerant fuel
BWR	Boiling water reactor
CANDU	CANada Deuterium Uranium
CEA	French Alternative Energies and Atomic Energy Commission (France)
EDF	Électricité de France (*Electricity of France*)
EOL	End-of-life
EPRI	Electric Power Research Institute (United States)
ERU	Enriched reprocessed fuel
HALEU	High-assay low-enriched uranium fuel
IAEA	International Atomic Energy Agency
JAEA	Japan Atomic Energy Agency (Japan)
LWR	Light water reactor
ML	Machine learning
MOX	Mixed oxide
NEA	Nuclear Energy Agency
NSC	Nuclear Science Committee (NEA)
OECD	Organisation for Economic Co-operation and Development
PWR	Pressurised water reactor
SG	Subgroup
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	Spent nuclear fuel
UOX	Uranium oxide
VVER	Water-water energetic reactor
WPNCS	Working Party on Nuclear Criticality Safety (NEA NSC)

Executive summary

Over the past decades the use of nuclear fuel has seen an increase in average assembly burn-up in connection with higher initial fuel enrichment as well as extended reactor cycle length. The spent nuclear fuel (SNF) decay heat, being its thermal power, is consequently modified compared to past ordinary values. Additionally, the use of mixed oxide fuel (MOX) and enriched reprocessed fuel (ERU) as well as the planned use of new fuel types (such as accident-tolerant fuel [ATF] and high-assay low-enriched uranium fuel [HALEU]) have led to calls for an improved understanding of the estimation of SNF decay heat. This is particularly relevant for the handling, storage and reprocessing or long-term disposal of the SNF.

Subgroup (SG) 12 of the Nuclear Energy Agency (NEA) Working Party on Nuclear Criticality Safety (WPNCS) was therefore launched in 2022 to find answers to several questions related to SNF decay heat, both from an experimental and a theoretical aspect. The main question that was addressed was: how well can SNF decay heat be estimated? This was followed by: what are the main quantities of interest for such an estimation? Additionally, questions linked to uncertainties, tolerance intervals as well as needs from the user's perspective were also studied. The past and current experimental facilities were reviewed, including direct and indirect methods (calorimeters, neutron and gamma measurements). The physics-based calculation practices, in standard methods or best-estimate codes were also presented with specific details. In addition, the advantages of new mathematical approaches, commonly denominated as machine learning (ML), in combination with more traditional practices, were explored.

The main recommendation from SG-12 concerns the need for new measurements of SNF decay heat, based on a calorimetric approach. The current experimental database contains measurements for SNF assemblies with lower initial enrichment and burn-up values compared to today's use of fuel assembly characteristics and concerns standard pressurised water reactor (PWR) UO_2 fuel. No public experimental data regarding decay heat are available for MOX fuel, as well as for water-water energetic reactor (VVER) or CANada Deuterium Uranium (CANDU) fuel types. SG-12 encourages new experimental initiatives in order to diversify measurement facilities, increase redundancy and provide public data for various types of fuel assemblies, following the Swedish approach. The second recommendation is to improve the current understanding of calculation methods with detail on the impact of relevant input parameters and their uncertainties. Comparisons between methods, practices and validation approaches would help to better assess the origin of possible discrepancies and understand differences between methods applied in various institutes. Finally, the use of ML methods was recognised as a resource for defining new measurements, optimising information gains and controlling costs.

1. Introduction

This report summarises the findings obtained by Subgroup (SG) 12 of the NEA Working Party on Nuclear Criticality Safety (WPNCS), which ran from January 2022 to January 2024. SG-12 was dedicated to assessing the confidence levels in experimental and computational estimations for existing spent nuclear fuel decay heat. The main conclusions of SG-12 are detailed in an extended publication (Rochman et al., 2024), and short descriptions of the main findings are presented in the following.

Decay heat from existing spent nuclear fuel (SNF) assemblies is one of the main quantities of interest for the characterisation of high-level nuclear waste, with implications for the safety and economics of their handling, storage and long-term disposal. It is also a relevant quantity for safeguard purposes, with consequences for fuel cycle decisions. SNF decay heat can be defined as the recoverable energy released from the decay of radionuclides during irradiation and after the reactor cycle's shutdown. It corresponds to the released thermal power, which is historically called "decay heat". Depending on the cooling period considered, the SNF decay heat can have various consequences. During cycle operation and up to its end, the decay heat can be approximately 7% of the total reactor heat source for a commercial light water reactor (LWR). In the seconds to days after operation (defined as short cooling periods of time), SNF decay heat can damage the primary and secondary safety barriers if not properly evacuated, resulting in the release of radioactive materials to the environment. Then, during cooling time, which can last from days to years, such decay heat must be considered for safe handling of SNF and its wet or dry storage; the design of storage pools, transport casks and surface dry pad storage must account for this potential hazard. Finally, for longer cooling periods, the SNF can be reprocessed or disposed of, and its decay heat needs to be accounted for in the design of such facilities.

The main parameters for the quantification of SNF decay heat, as recognised in past studies and confirmed by SG-12, are summarised below.

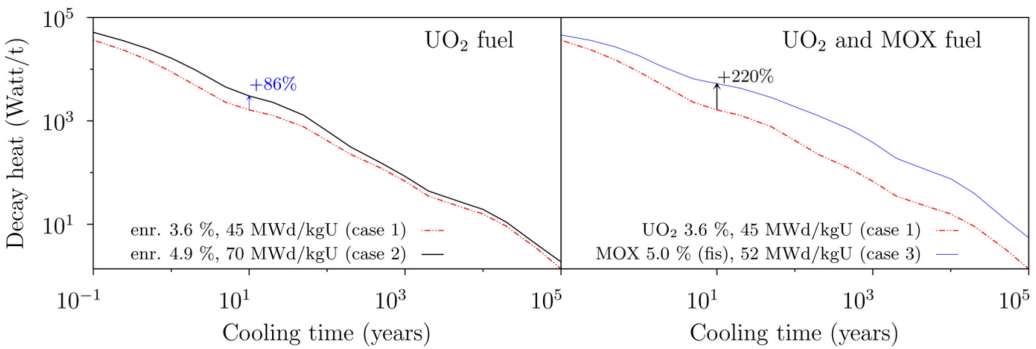
- The integral fuel irradiation level or burn-up (in MWd/t): In the case of the SNF assemblies, such burn-up value is obtained from core simulators and can be experimentally checked with gamma or neutron measurements.
- The initial fuel composition, including its enrichment and initial mass of actinides: Such values are also generally provided by the reactor operator.
- The cooling time, calculated as the difference between a date of interest and the date of the end-of-life (EOL); this is also provided by the reactor operator.

With these three quantities, the SNF decay heat can be relatively well calculated, given that the above quantities are precisely known. Additionally, for specific cases, as well as for more accurate calculations, the effect of the following quantities can also be discussed:

- the fuel assembly irradiation rate (in MW/t) during the reactor operation, which is especially important for short cooling times (e.g. just after the reactor shutdown or during the fuel unloading);
- the use of burnable poisons (mainly during the first irradiation cycle), which can be important for partially irradiated assemblies, as possibly used in the last reactor cycle;
- other manufacturing and irradiation parameters (such as dimensions, densities, temperatures, void).

The first justification for developing new efforts towards a re-evaluation of the decay heat prediction capabilities lies in the fact that nuclear fuel design and usage have changed as the nuclear industry has evolved over time. The initial enrichment has been steadily increased to 5.0% in ^{235}U for UO_2 fuel, and the assembly average burn-up currently can reach 70 MWd/kg ($U_{initial}$) or higher. This is a significant shift in practice compared to the years before 2000, when the initial fuel enrichments for UO_2 fuel rarely exceeded 3.8% in ^{235}U, with average assembly burn-up values generally lower than 55 MWd/kgU. Additionally, the use of mixed oxide (MOX) fuel has been regularly increased in some countries, whereas other countries also possess MOX SNF stored from past use. An example is presented in Figure 1 for typical assemblies used before the year 2000 (low enrichment, low burn-up; see the curve labeled "case 1") and 20 years later (higher enrichment, higher burn-up; see curves labeled "case 2" and "case 3"). The increase in initial enrichment and EOL burn-up generally pushes the decay heat to higher values for an extended period of cooling time. In the case of UO_2 fuel, it is possible to see in the example a significant increase in decay heat between cases 1 and 2, especially for cooling time from 1 to 100 years.

Figure 1. **Examples of calculated decay heat for typical UO_2 assemblies having different burn-up and enrichment values (left); comparison between typical MOX and UO_2 SNF assemblies (right)**



Note: Cross-sectional view of corium layers: the material properties at any spatial location are known only statistically.

This has consequences for the storage of SNF assemblies: between 1 and 100 years of cooling time, such SNF assemblies may potentially be moved more than once from one place to another and eventually from cask to canisters, with canisters going into long-term repository. Accordingly, new calculations are needed for the current stockpile of SNF assemblies, implying new validation efforts, hopefully based on new (or re-analysed) decay heat measurements. As presented in the same figure (right part), the decay heat coming from MOX fuel is also higher than for UO_2 fuel, mainly due to higher contributions of minor actinides to the decay heat. Additionally, there are no available direct decay heat measurements at the MOX or enriched reprocessed fuel (ERU) assembly level, making the validation of calculations with direct measurements unfeasible (MOX fuel will lead to higher minor actinide concentrations, whereas ERU file will lead to higher ^{238}Pu content at EOL). The precise knowledge of the decay heat for various values of the main three parameters presented above (fuel with low and high initial ^{235}U enrichments, low and high burn-up values, and short and long cooling times) directly affects the safety and economy of the back end of the fuel cycle, therefore incentivising nuclear industry stakeholders to understand decay heat values, as presented in Figure 1.

The second justification for new efforts in the prediction of SNF decay heat comes from the need for reduced uncertainties and well-assessed biases in measurements and calculations. This stems from stringent safety rules and higher economic constraints. Estimations of uncertainties from many input parameters of relevance can nowadays be conveniently obtained, affecting the knowledge and understanding of decay heat calculated values. There is consequently a global effort to reduce uncertainty, based on better knowledge of many input parameters. Finally, a third justification for the reassessment of the SNF decay heat originates from the need for a larger experimental database for the purpose of validation. Most measurements for SNF decay heat come from the Central Interim Storage Facility for Spent Nuclear Fuel (Clab) in Sweden, with additionally a limited number of cases from two decommissioned American facilities (with significantly higher experimental uncertainties). While it is an advantage to access these measurements and all necessary information on the irradiated assemblies, there is an inherent risk in using experimental values that come from a single facility as possible correlations between measured values are not mitigated with other experimental sources. Additionally, as mentioned, these measurements do not cover all the characteristics of current SNF assemblies in terms of initial enrichment, burn-up and fuel type.

Given the consequences of SNF decay heat in various fields of the fuel cycle back-end, as well as the various possibilities for the origins of the SNF assemblies, the primary focus of SG-12 was on existing SNF assemblies from current LWRs, with the main goals described below.

- To allow interested participants to exchange their experience related to the prediction of SNF decay heat (current knowledge, interests and needs); such participants come from different actors of the nuclear sector: research entities, waste management organisations, utilities, technical support organisations, as well as safety authorities.
- To provide a state-of-the-art report for the estimation of the decay heat from existing SNF (see the extended report presented in [Rochman et al., 2024]), including an overview of the calculation capabilities, possible sources of uncertainties and a description of the available experimental data, which would recapitulate the knowledge acquired over the past decades, as well as the status of understanding, measurements and simulations, including foreseen future needs.

- To raise awareness of the relevant needs in terms of calculations and measurements, when applicable.
- To provide recommendations to improve SNF decay heat estimation, with respect to measurements, simulations, input information and best practices. These recommendations are detailed in (Rochman et al., 2024) and are also shortly presented in this report.

It is worth mentioning other parallel studies on the SNF decay heat, such as the International Atomic Energy Agency (IAEA) Co-ordinated Research Project on Spent Fuel Characterisation (2020-2024) (IAEA, 2025), as well as the activities of the European Union Joint Strategic Programme of Research and Knowledge Management dedicated to supporting radioactive waste management studies, EURAD (2019-2024) (European Union, 2025). As mentioned hereafter, ongoing transnational projects between the Electric Power Research Institute (EPRI) and Swedish Nuclear Fuel and Waste Management Company (SKB) will provide information on new decay heat measurements. Such initiatives are especially welcome, given the scarcity of experimental data. Finally, the development of national projects, not finalised within SG-12, can lead to the building of new calorimeters, thus sensibly improving the experimental capability for direct decay heat measurements.

2. Motivation

The capability to calculate SNF decay heat and provide well-justified uncertainties and biases has direct implications for the simulation of accident scenarios, the safety of the back end of the fuel cycle, and the costs involved. To improve such estimations has been the main motivation for establishing SG-12 and presenting the state-of-the-art measurements, simulations and validation. The work of the SG-12 had two main priorities, as described below.

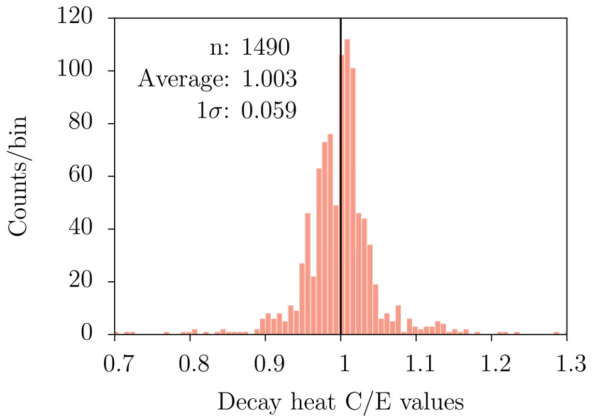
- It sought to raise awareness of the need for new and independent measurements of SNF decay heat. When the SG-12's work began the limited number of such measurements was directly affecting the confidence level of simulations. Such experiments were expensive and only one facility existed worldwide. The domain of direct validation is therefore restrained, potentially leading to increased safety margins.
- SG-12 sought to improve understanding of the different possibilities in simulations and the impact of different parameters. Various methods, guidelines and recommendations exist among institutes and countries, leading to different calculated decay heat values, even when starting from the same measurement database. Such variation in the results should be made visible and explained for specialists and non-specialists. Additionally, different validation procedures can also have different impacts on application quantities. Making such differences explicit and understanding them is one of the main motivations of the SG-12 work.

To illustrate the current capabilities of simulation codes and the need to improve them, Figure 2 represents one aspect of the validation of codes used in the calculations of SNF decay heat.

Figure 2 presents the histogram for the calculated over experimental values for SNF decay heat coming from calorimetric studies. Tabulated values from the open literature are used for this figure, mixing pressurised water reactor (PWR) and boiling water reactor (BWR) assemblies, different simulation codes, nuclear data libraries, calculation procedures, and experimental sources. Such results do not come from validated procedures but are rather a snapshot of the published data. In total, 1 490 calculated over experimental ratios were found, with an average of 1.003, with a standard deviation of 0.059. It indicates that the simulation capabilities can satisfactorily reproduce measured decay values for SNF with calorimetric measurements. One standard deviation is found to be close to 6%, and almost 86% of the data are within $\pm 1\sigma$. By considering two standard deviations, almost 97% of the cases are covered; a three-sigma interval leads to 98.8% of the cases (five sigmas cover 99.6%). Depending on the application, such numbers can be considered as adequate or not. Nevertheless, it is important to understand the limitations of the experimental database used to perform such a validation. If a specific application requires that more than 99% of the cases be covered, it is necessary to consider 3σ for the PWR SNF assemblies (corresponding to 1.000 ± 0.138), and 5σ for the BWR SNF assemblies

(corresponding to almost 1.009 ± 0.395). Such large uncertainties, in terms of standard deviations, can have important consequences for facility designs, and it is therefore of high interest to improve the predictive capabilities. Consequently, there is a strong need to reduce such uncertainties with well justified arguments.

Figure 2. **Histogram of the ratios of calculated (C) over experimental (E) decay heat values from literature studies for calorimetric measurements of full fuel assemblies**



Note: Cross-sectional view of corium layers: The material properties at any spatial location are known only statistically.

Additional information is provided in Rochman et al. (2024) regarding experiments, theoretical methods for decay heat calculations, codes, standard methods and validation.

3. Recommendations

Based on the current understanding of the physical phenomena at stake in the decay heat for current spent nuclear fuel assemblies, the following recommendations are proposed by SG-12. This list is not comprehensive but represents the main priorities recognised at the time of writing.

- Extension of the current experimental database: The current experimental database of direct decay heat measurements (with a calorimeter) is relatively small; it is in practice fully dependent on values provided by the Central Interim Storage Facility for Spent Nuclear Fuel (Clab) in Sweden. New measurements on different fuel types, possibly at a different facility, would greatly improve the situation.
- Improvement of theoretical understanding and nuclear data: If the methods to calculate SNF decay heat are well known, their application may vary from code to code. Validated procedures may also differ between institutes, based on best-estimate codes or on standard methods. Specific nuclear data libraries can be required by a validation procedure, with values not directly accessible by users (such as available energy release per fission). Such aspects need to be discussed for a better understanding (and eventually an improvement) of the decay heat calculations.
- Best-estimate calculations and conservative estimations: Linked to the previous recommendation, it is necessary to separate cases where a best-estimate code and standard methods are applied. If one is not conservative by nature, the other one might unsystematically lead to high decay heat values. Additionally, different conservative methods (or standard methods) contain different levels of approximations, and users need to be aware of possible drawbacks of the method they use.
- Biases and uncertainties: Finally, the estimation of biases (in terms of differences between a reference value and a value from a given procedure) needs to be obtained and considered along a complete calculation chain, up to the final quantity of interest. Similarly, uncertainties must be considered, with clear definitions of underlying assumptions. In addition, for a complete understanding of the results, the mathematical method used in the analysis also needs to be presented.

The list of recommendations can be extended to many other features, most of them not only applicable to decay heat calculations and not solely linked to simulation methods. Such aspects include but are not limited to:

- Redundancy: It can mean the repetition of the same measurement at the same facility (as performed in a number of cases at the Clab facility), but also measurements of very similar SNF assemblies in different facilities.

- Comparison of code implementations: The coding of identical mathematical methods can often be performed in different ways due to a variety of solvers, code languages, available libraries, approximations or assumptions. The comparison between different code implementations of the same method (e.g. the summation method) can be part of a validation procedure, avoiding unexpected inaccuracies or miscalculations.
- Blind benchmarks: Comparisons between calculated and measured values, as presented in Figure 2, are often based on calculations performed while the target values (experimental values) are available. This may lead to adjustments of calculation inputs to improve the agreement. An efficient procedure to decouple predictions from actual measurements will perform blind calculations. Additionally, making available all code inputs and outputs allows for more understanding of results and calculation methods.
- User effect: Finally, the impact of modellers performing the calculations (assuming a number of quantities, as well as performing simplifications) is often underestimated. It was observed that results between different institutes, based on the same codes and presumably input descriptions, can differ by unexpected amounts. It is necessary to be aware of such a potential source of error and eventually quantify it.

4. Conclusions and latest developments

The activities performed within Subgroup 12 (SG-12), started in January 2022 and ended in January 2024 under the auspices of the NEA Working Party on Nuclear Criticality Safety (WPNCS), which aimed to describe the current knowledge on decay heat (or thermal decay power) for existing spent nuclear fuel (SNF) assemblies. The main findings were described in an extended publication (Rochman et al., 2024). Several different areas were reviewed: theoretical description, simulation, standard methods and measurements. One of the motivations for this work was to address the needs of the nuclear sector for the estimation of decay heat during short-term cooling (such as in core transient) and up to the back end of the fuel cycle (SNF wet and dry storage, up to and including final repository). This initiative was necessary to address recent changes in the sector's needs due to higher initial fuel enrichment and higher assembly burn-up.

Analytically, it was acknowledged that the existing set of decay heat measurements is highly valuable yet limited. This limited availability has two main consequences: (1) All recent (and eventually new) measurements come from a single facility, rendering redundancy and independent checking impracticable; and (2) all recent (and eventually new) measurements are performed on a limited set of SNF assemblies, corresponding to those stored at the Clab facility in Sweden.

From the simulation point of view, new needs related to existing SNF assemblies mainly arise from stringent economical requirements and ever stricter safety rules related to core transient, extended storage and deep geological repository. When possible, direct validations (mostly for cooling times of less than a few decades) are still necessary, but for periods of interest to deep geological repositories, other questions may come to light. The improvements in calculated decay heat values sought to provide a better understanding of experimental methods and uncertainties, a better assessment of key parameters for simulations (such as the burn-up), and also to make use of various sources of information not directly linked to decay heat, such as post-irradiation experiments and full core simulations.

Another important international project covers the measurements and the evaluations of decay heat at the Clab facility in Sweden. It is a collaboration between the Swedish Nuclear Fuel and Waste Management Company (SKB), Vattenfall and the Electric Power Research Institute (EPRI) (including, but not limited to, the new SKB-50 measurement campaign, as studied in the European project EURAD, Work Package 8 on Spent Fuel Characterisation). When completed, one of the outcomes of this project will be the measured decay heat for a number of new SNF assemblies, as well as the necessary information required to perform decay heat calculations. This study will also include a review of the past Clab measurements, with possible modifications on the reported measured values. New analysis and validation studies will therefore be necessary, with new impacts on the estimation of the SNF decay heat.

Regarding experiments, two new projects are under development and were presented at the time of the activities of SG-12: the French and Swiss calorimeters. The first one is dedicated to measurement at the level of the assembly rods and pellets (and is led by the French Alternative Energies and Atomic Energy Commission [CEA] and Electricité de France [EDF]); the second one is designed for full assembly measurements (to be performed at the Gösgen power plant). These projects were not finalised at the time of SG-12 activities.

Finally, in addition to the need for new measurements combined with analysis based on physics codes, there is growing interest in modern advanced mathematical methods combined with powerful calculation capabilities, commonly called machine learning (ML). It has recently been shown that such methods can help identify experimental gaps, define the most relevant measurements to be performed, and indicate experimental outliers. With respect to validation, ML techniques, when combined with physics analysis, can assist in separating random and systematical discrepancies. In the future, the combination of best-estimate physics codes with such mathematical methods can significantly improve the efficiency of validation analysis.

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Summary of the NEA Assessment on Spent Nuclear Fuel Decay Heat for Light Water Reactors

This report summarises the NEA assessment of spent nuclear fuel (SNF) decay heat for light water reactors, which highlights the increasing importance of accurate decay heat estimations due to evolving fuel characteristics. Over the past decades, the nuclear industry has seen higher initial fuel enrichment, increased burn-up rates, and extended reactor cycle lengths. This necessitates a refined understanding of decay heat for safe handling, storage, reprocessing and disposal of SNF.

Subgroup 12 (SG 12) of the NEA Working Party on Nuclear Criticality Safety (WPNCS) was established in 2022 to evaluate the accuracy of SNF decay heat predictions. The group examined experimental methods, computational models, and uncertainties in decay heat estimation and emphasised the need for new calorimetric measurements due to a lack of data for fuel types such as mixed oxide (MOX), water-water energetic reactor (VVER), and CANada Deuterium Uranium (CANDU).

This report's recommendations include expanding experimental databases, improving theoretical models, and integrating machine learning (ML) for validation. Future studies will focus on enhancing simulation accuracy, reducing uncertainties, and refining safety assessments for long-term SNF management.

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