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RESEARCH REPORT VTT-R-00243-25

SMRSiMa:

SMR Waste Management and Siting

Waste characteristics and organisational aspects

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Version: 14.05.2025

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Report's title	
SMRSiMa: SMR Waste Management and Siting, Waste characteristics and organisational aspects	
Customer, contact person, address SAFER2028 Research Programme	**Order reference** SAFER2028 programme 2024
Project name SMRSiMa SMR Waste Management and Siting	**Project number/Short name** 136018 SMRSiMa
Author(s) Sami Naumer, Paula Keto, Nadezhda Gotcheva, Pauli Juutilainen, & Merja Airola,	**Pages** 25
Keywords SMR, spent fuel, waste characteristics, waste management, organisational models, oversight of organisational aspects	**Report identification code** VTT-R-00084-24

Summary

Small modular nuclear reactors (SMRs) are seen as one solution for producing low carbon energy and heat. What effect SMR technologies have on waste characteristics and disposal, how the management could be organised in practice as well as societal engagement have been studied in Finland as part of the national research programme SAFER2028 National Nuclear Safety and Waste Management Research Programme 2023–2028. The focus of the work has been on SMRs based on light-water technology.

One key element that has been studied with numerical modelling is the potential effect of the smaller reactor core size of SMRs on spent fuel characteristics. In order to do this, multi-cycle full-core 3D calculations were performed with Serpent – Ants sequence. Preliminary results with the case study (LDR lite benchmark) indicate that the axial burnup profile does not have any flat segment, in contrast to those of large PWR cores, but the impact on the integral features of spent fuel assemblies seemed to be small. However, further post-processing will be needed to, e.g., verify the impact on spent fuel reactivity for criticality safety analysis and to segregate the effect of modelling accuracy against computational issues.

Organisational models for arranging the SMR waste management in Finland are generally regulated by the Finnish Nuclear Energy Act and Directive 2011/70. The renewal of the Nuclear Energy Act is ongoing. The study discusses different models for organising and financing SMR waste management including models that are applicable and in use currently, but also alternative models that are not in line with the current Nuclear Energy Act. Alternative models are limited, e.g., by import and export bans and partly also by formulation of the waste management obligation (in the case of fuel leasing agreements). The applicability of any organisational model will also depend heavily on the sufficient expertise of the organisation and robustness of the business case.

This study also identifies potential challenges in regards to the safety oversight of organizational, management, and leadership aspects throughout the SMR lifecycle. It includes a review of existing public material, and four future scenarios based on interviews with Finnish nuclear experts. These findings were discussed with STUK and the OECD NEA Working Group on Human and Organizational Factors (WGHOF) SMRs task group.

Confidentiality	VTT Public

Espoo 14.5.2025

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Preface

This report was compiled between August 2024 and January 2025. It presents work conducted in Work Packages 1, 2 and 4 in the SAFER2028 funded SMRSiMa project. It is a continuation of the KYT2022 funded SMRWaMa and SMRSiMa projects with the objective to study Small Modular Reactor (SMR) related waste management, siting and societal engagement aspects. The project belongs to Technical Advisory Group (TAG) 3.3 - Rock, Site and Biosphere where project progress and schedule were followed and feedback on future efforts provided in two TAG meetings during 2024.

The SMRSiMa work produced during 2023 - 2024 was disseminated in VTT Research Report VTT-R-00084-24 Waste Management and Social Engagement (Naumer et al. 2024). Based on this work, conference papers were submitted to IAEA (International Conference on Management of Spent Fuel from Nuclear Power Reactors: Meeting the Moment, 10 -14 June 2024, Vienna Austria) and OECD NEA (NEA Safety Case Symposium 2024) meetings. Both papers "*Adapatation of current final disposal strategy and methods in Finland for spent fuel from SMRs*" by Keto et al. (2024a) and "*Considering Disposal of Spent Fuel from SMRs and Next Generation Reactors in Finland*" by Keto et al. (2024b) were accepted for publication (pending). We would like to thank all who have contributed to these papers, especially Linda Kumpula (TEM), Ville Koskinen (STUK) and Posiva Oy.

Additionally, special thanks to Linda Kumpula, Ville Koskinen and Annukka Laitonen (TVO) for giving comments to the chapter concerning organisational models and their compatibility concerning the regulatory framework.

Stakeholder interviews on SMR-related plans and research needs were held together with representatives from TVO, Fortum and an expert from LUT. We thank all of you for the valuable discussions and contribution to the results presented in this report. We also thank Timothy Schatz (VTT) for reviewing this report.

Finally, we would like to thank the members of TAG 3.3, especially SAFER2028 Director Suvi Karvonen and TAG3.3 Chair Antti Poteri for the advice and interest in our project.

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1. Introduction

1.1 Background and objectives

Finland aims for carbon neutrality by mid-2030 (MEAE, 2022a); the target at the EU level is by 2050. Nuclear power is seen as one alternative for meeting these targets. While electricity can be produced at locations further from urban areas, the use of SMRs in district heating applications may require siting of the plants closer to populated areas. The reactor capacity in the district heating application is envisioned to be relatively small (e.g., LDR-50 unit with capacity up to 50 MW thermal). Municipalities in Finland currently considering SMR-technology for heating or electricity production are Helsinki, Espoo, Kuopio and Tornio. The municipalities are geographically distant from each other and could, in principle, have different licence holders and selected SMR technologies. The licence holder producing the waste is responsible for waste management and its cost, arranging the waste management may require domestic or international cooperation to ensure that the organisation has sufficient expertise to take care of the waste management.

Previously identified generic waste management strategies include centralised, local and hybrid waste management for spent nuclear fuel and LILW (Keto et al., 2022). One objective of this work is to map and discuss different organisation models for waste management in Finland and their compatibility with the current Nuclear Energy Act and EU directive 2011/70. While the Finnish Nuclear Energy Act is currently under renewal, implications to the organisational models cannot be yet fully analysed. This remains to be performed in the final year of the SMRSiMa project.

One objective is to identify potential challenges and pitfalls in the regulatory safety oversight of organizational, management, and leadership aspects throughout the lifecycle of SMRs. This work consists of a short review of existing public material on the topic and four scenarios regarding the “desired future of SMRs” based on interviews with Finnish nuclear experts. Additional discussions with STUK and OECD NEA WGHOF representatives highlighted the importance of clearly defining the roles and responsibilities of the license holder and operator in the context of SMRs, as well as the link between organizational design and safety management. Ensuring safety and effective management requires a thorough understanding of these roles and their interactions.

The characteristics of SMR spent fuel do not significantly differ from that of large reactors, when the same reactor and fuel types and similar fuel discharge burnup are considered. The topic was discussed previously by Keto et al. (2022), in which spent fuel properties were compared between large (EPR) and small reactors (NuScale, LDR) based on 2D assembly calculations using Serpent (Leppänen et al., 2015).

The potentially interesting point regarding SMR spent fuel characteristics is the impact of the smaller core size and the related smaller inner-to-outer core volume fraction, leading to larger neutron leakage, if it is not curbed with applicable technical methods. In order to capture any impact, full-core neutronics calculations were performed with the Kraken reactor analysis framework (Leppänen et al., 2022) utilizing the LDR lite benchmark model. The reactor was modelled over a sufficient number of operating cycles that the equilibrium core was reached with sufficient accuracy, meaning that the discharge burnup of each assembly and the cycle lengths converged to a near constant level between consecutive cycles.

SMR waste management, siting of SMR plants, societal acceptability and stakeholder involvement has been studied previously in Keto et al. (2022, 2023), Naumer et al. (2023) and in Keto et al. (2024a, 2024b).

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2. Work Package 1 (WP1) SMR Spent fuel characteristics

2.1 Spent fuel characterisation for SMR

For the computational exercise to calculate spent fuel inventories with a full-core 3D calculation, the equilibrium cycle of the LDR lite benchmark (Komu and Tuominen, 2023) model was used. The LDR lite is an open-access model for research purposes. It is based on the LDR-50 reactor designed for district heating with the thermal power of 50 MW. The inventories were calculated using the Serpent – Ants computing sequence, in which the Monte Carlo code Serpent was used to generate the homogenized group constants for the nodal neutronics solver Ants (Sahlberg and Rintala, 2018; Kähkönen, 2024). The group constants were generated as part of the comparison of Serpent vs. Serpent – Ants sequence for the initial core of the LDR lite (Kähkönen, 2025). The initial core partly consists of the same fuel assembly types as the equilibrium cycle core, but a few other assembly types are additionally used in it. The multi-cycle simulating feature was tested and reported in (Valtavirta, 2025), but this analysis did not involve the micro-depletion mode of Ants. The computational model for the analysis presented in this section was constructed as a combination of these models. The Serpent 2D reference results are based on the models used in (Keto, 2022).

The LDR lite core consists of 37 fuel assemblies, each 17 x 17 pins, out of which 25 slots are control rod or instrumentation tubes. In equilibrium, the fuel assemblies are irradiated over three cycles, except the central assembly that is irradiated over one cycle only. The U-235 enrichment is 1.5 wt-% for the one-cycle assembly and 2.4 wt-% in the others. Every assembly contains 8 gadolinium (Gd) rods, but the Gd content varies: in the 1.5 % U-235 assembly the mass fraction of Gd is 6.0 % and in the 2.4 % enriched assemblies it is either 5.0 % or 9.0 %. In contrast to typical PWRs, no boron is used, so control rods are actively used to adjust the core reactivity.

2.2 Computational models

In Serpent calculations, the core parameters were assumed to stay constant over irradiation, such as fuel temperature 561 K (288°C) and clad and moderator temperature 404 K (131°C). The calculations did not involve any control rod presence. The total thermal power of 50 MW was converted to a linear power of 10.7 W/gU. It may be noteworthy that these temperatures were slightly lower in the original calculations, but the calculations were re-run in order to make the temperatures match with those used as the nominal state in the group constant calculations. Furthermore, the nuclear data was matched, i.e., JEFF-3.2 cross-section and JEFF-3.1 fission yield and decay data were used.

As mentioned above, the Ants takes the group constants calculated by Serpent as an input component to provide the averaged neutronics properties for each user-defined volume segment. In addition to the Serpent – Ants sequence, the core calculations also employ other components of the Kraken framework, namely the thermal-hydraulics solver Kharon and the fuel behaviour solver SuperFINIX to take into consideration the feedback between neutronics, thermal hydraulics and fuel behaviour. Core criticality is achieved with a control rod iteration functionality that adjusts the regulating control rod heights such that in addition to make the core critical (k_{eff} = 1.0), the radial power distribution would be as flat as reasonably possible. The cycle is terminated when the core remains subcritical with all control rods fully withdrawn. A fuel depletion step of 25 days was used over most of the cycles, but in order to iterate the end of the cycle more accurately, a 5-day depletion step was used when approaching the anticipated end of the cycle.

In the multi-cycle simulation to search for the equilibrium cycle, the initial core loading partly consists of special fuel assembly types, but after the first cycle, the removed assemblies are replaced with the equilibrium cycle assemblies. Equilibrium was considered to be achieved when the cycle length and assembly-average burnup between the cycles converged to sufficiently constant values. This took roughly 10 cycles. However, the selection of the predictor-corrector approach in the Ants depletion calculation somewhat affected the convergence speed and final stability, but ultimately the impact of it can be

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considered negligible in the context of spent fuel characterization for waste management purposes. The equilibrium cycle length was observed to vary between 545 and 550 days at convergence.

The reloading scheme and the assembly identifiers (A<N>, N = {1…8}) used in the result analysis are illustrated in Figure 1. The assembly types are illustrated with the background colour coding of each assembly and the circle colour informs whether the assembly is removed or continues to be irradiated over one or two cycles. In the figure, FA<N> provides the assembly identifier to follow its path through its irradiation history, as the related C<N> label in the assembly identifies the number of cycles (N) the assembly was irradiated.

In the original Serpent calculations, the fuel depletion steps were defined in terms of assembly burnup, i.e., steps defined in MWd/kgU. For reference, complementary calculations were performed for each assembly type using depletion steps defined in days so that 550 days was assumed to be the cycle length. This was considered to sufficiently match the equilibrium cycle length obtained from Ants calculations.

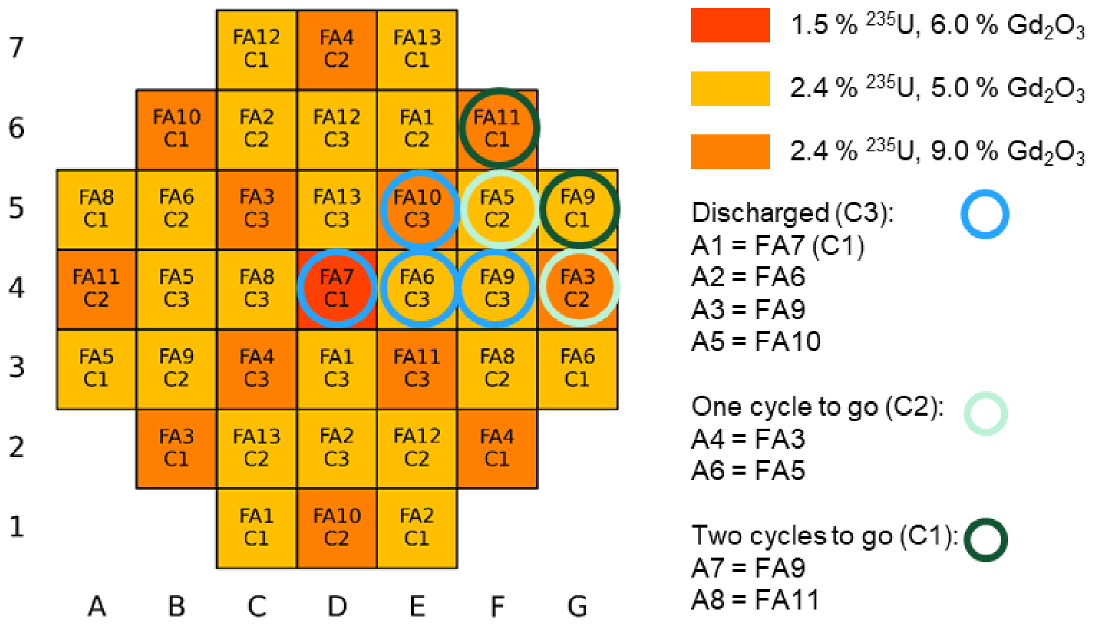

Figure 1. The reload pattern of the LDR lite equilibrium core. The colour-coded circles mark the number of cycles the assembly was irradiated, except for the central assembly that is irradiated over only one cycle. A<N> refers to the identifier of the assembly used in the post-processing for the 1/8 core symmetry slice. (Valtavirta, 2025)

2.3 Results

Ants provided the spent fuel inventories at the end of cycle. The inventories were compiled to Serpent material card format to allow the post-irradiation decay calculations to be performed with Serpent to produce the inventory development over time, as well as the derived features, such as radioactivity and decay heat power. The spent fuel compositions were averages over each assembly, but average burnup data was also extracted for each axial segment. The segments were mostly 5.5 cm long, except for one around the mid-core at 5.7 cm.

The average burnup of each assembly at the end of an arbitrary equilibrium cycle is presented in Table 1. The assembly references are based on the Ants post-processing notations as presented in Figure 1. The column “mid-life” refers to the assemblies that have been irradiated over either one or two cycles: A4 and A6 have been irradiated two cycles and 7 and A8 have been irradiated over one cycle. These values were obtained with a 15-cycle simulation using the constant extrapolation and no interpolation as predictor and corrector in Ants fuel depletion calculation. However, as mentioned above, the differences caused by the predictor-corrector settings were negligible. The table also presents the calculated final burnup by Serpent, when its depletion history was defined as day steps.

Table 1. Average assembly burnups at the end of the cycle by Ants, A1-A8 as presented in Figure 1. For reference, end-of-life burnup after the Serpent 2D assembly calculations using day step burnup history is also presented.

Discharged	**MWd/kgU**	**Mid-life**	**MWd/kgU**
A1 (central)	6.43	A4	9.95
A2	18.09	A6	11.20
A3	18.03	A7	4.30
A5	16.84	A8	4.94
Serpent			
550 days	5.89	one cycle	
1650 days	17.66	three cycles	

The burnup profiles based on the average burnup of each axial segment of Ants calculation are presented in Figure 2. The curves illustrate the peaking factor, or deviation from the average burnup. It can be seen that the axial burnup shape is relatively equal for all assemblies regardless the time or duration in the core, which practically indicates that the control rod iteration has achieved a relatively even radial power distribution. Concerning the potential impact of small core size and active control rod usage on spent fuel properties, a somewhat large axial variance in discharge burnup can be observed. By contrast, history data available from French (IRSN, 2017) and Swedish (Agrenius, 2010) PWRs suggests that on average, the normalized burnup is well below 1.2 and rather constant between the end segments.

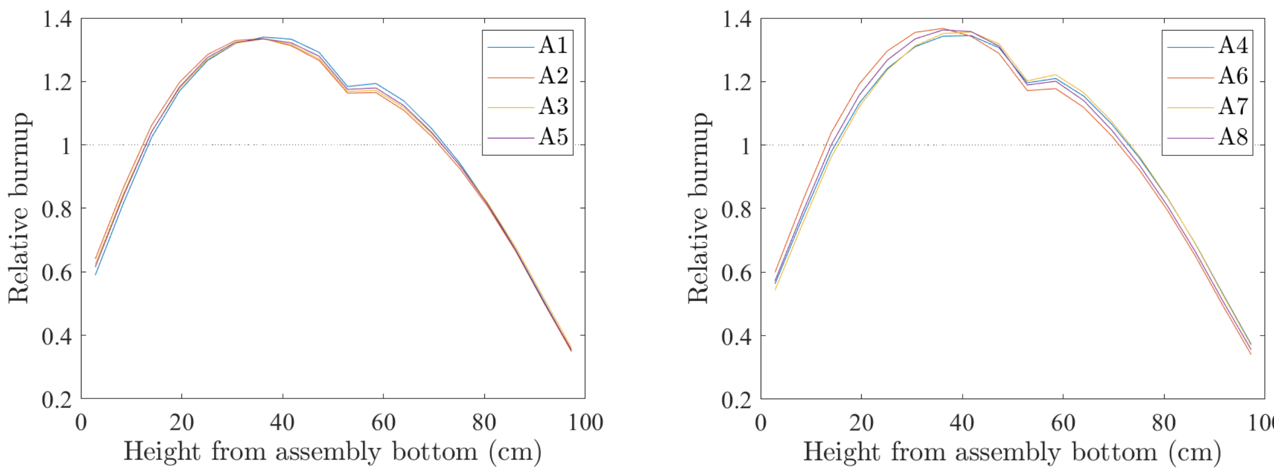

Figure 2. Axial burnup profiles with respect to the average burnup of each assembly. Discharged assemblies in the left figure, mid-life assemblies in the right.

Assembly-wise decay heat for 2.4 wt-% U-235 and 5.0 wt-% Gd_2O_3 is depicted in Figure 3. The differences are rather minimal: the Ants-based calculation predicts 20 % higher heat generation immediately after discharge, but the difference drops to less than 5 % after approximately 5 years. A major discrepancy appears roughly from 30,000 to a million years after discharge, but the heat generation as such is very small anyway, so it is a relative difference with no significance in absolute heat generation. The heat power behaviour between Ants and Serpent calculations with 9 % Gd_2O_3 was rather similar in terms of how the difference evolved over time, but the numbers varied somewhat. These relative differences are depicted

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in Figure 4 with the Serpent 2D models as the reference to illustrate the differences before the visible gap in absolute heat generation curves, i.e., up to ~24,000 years.

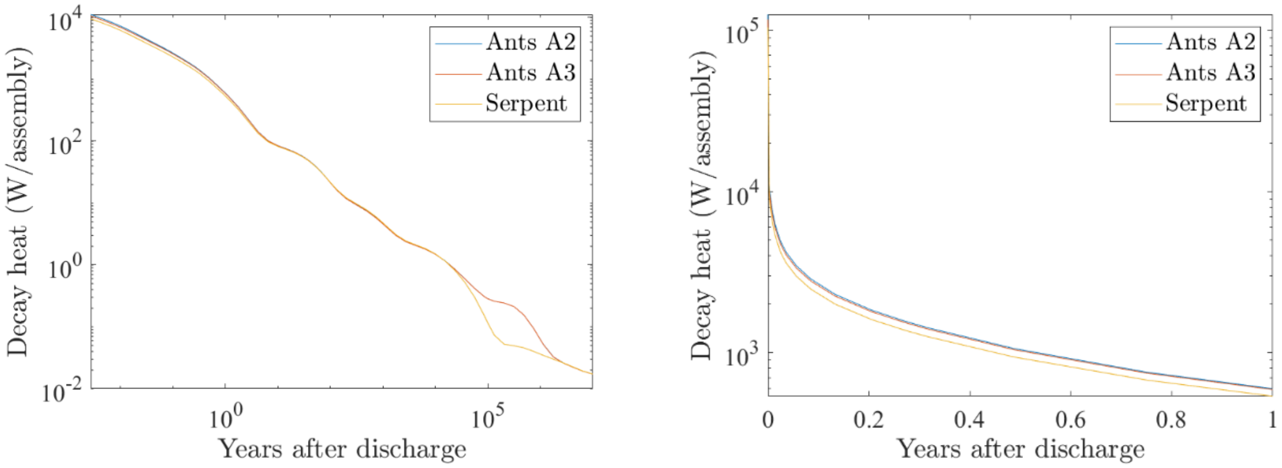

Figure 3. Decay heat power after irradiation for fuel with 2.4 % U-235 enrichment and 5.0 % Gd_2O_3 over the entire decay-calculated period (left) and the first year after irradiation (right). Note the logarithmic scale.

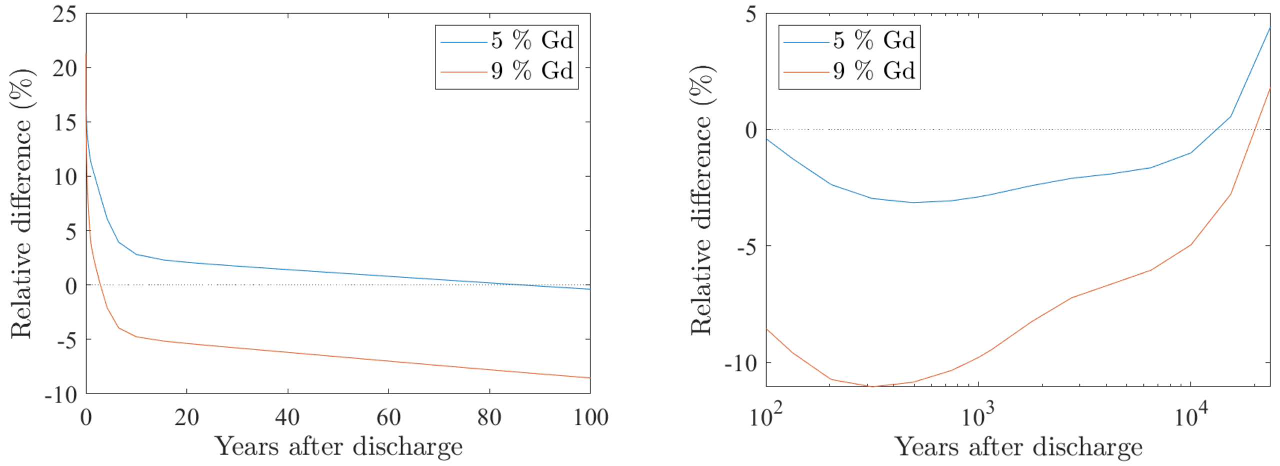

Figure 4. Relative difference between the decay heat power predicted by Ants and Serpent. Ants assembly A2 was used to represent 5 % Gd fuel and A5 the 9 % Gd fuel. The corresponding Serpent 2D assemblies were used as the reference.

The main decay heat contributing nuclides in the middle of the largest discrepancy (at roughly 200,000 years) are listed in Table 2. The top 4 are equal between Serpent and Ants (A2). The 5th largest heat producer is Pu-239 according to Serpent, but it is not one of the top 7 heater producers in Ants results. These differences may be interesting for criticality safety evaluations. Serpent calculations to determine the post-irradiation k_{eff} using the Ants output were not possible for this study, so they are to be performed in the future. However, when the inventories of the so-called actinide-only burnup credit nuclides[1] are considered, the codes indeed showed some disagreement. Some examples are provided in Figure 5, but the transport calculation for the spent fuel is needed to quantify the impact of these differences on criticality safety.

[1] Refers to burnup credit approach, in which the set of actinides are taken into account in spent fuel criticality calculations. In US NRC's Interim Staff Guidance – 8, Revision 3, "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transportation and Storage Casks", these nuclides are U-234, U-235, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242 and Am-241.

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Table 2. Comparison of the largest decay heat contributing nuclides between Serpent and Ants (A2, 5 % Gd fuel) at 205,370 years after discharge.

Serpent 2D	Heat power (W/cm)	Ants	Heat power (W/cm)
Po-214	5.459E-05	Po-214	4.0760E-04
Po-218	4.261E-05	Po-218	3.1817E-04
Rn-222	3.896E-05	Rn-222	2.9094E-04
Po-210	3.769E-05	Po-210	2.8143E-04
Pu-239	3.675E-05	Ra-226	2.5346E-04
U-234	3.504E-05	Th-230	2.4761E-04
Ra-226	3.394E-05	U-234	2.4285E-04
Top-7 share of total heat generation (%)	**53.4**		**84.1**

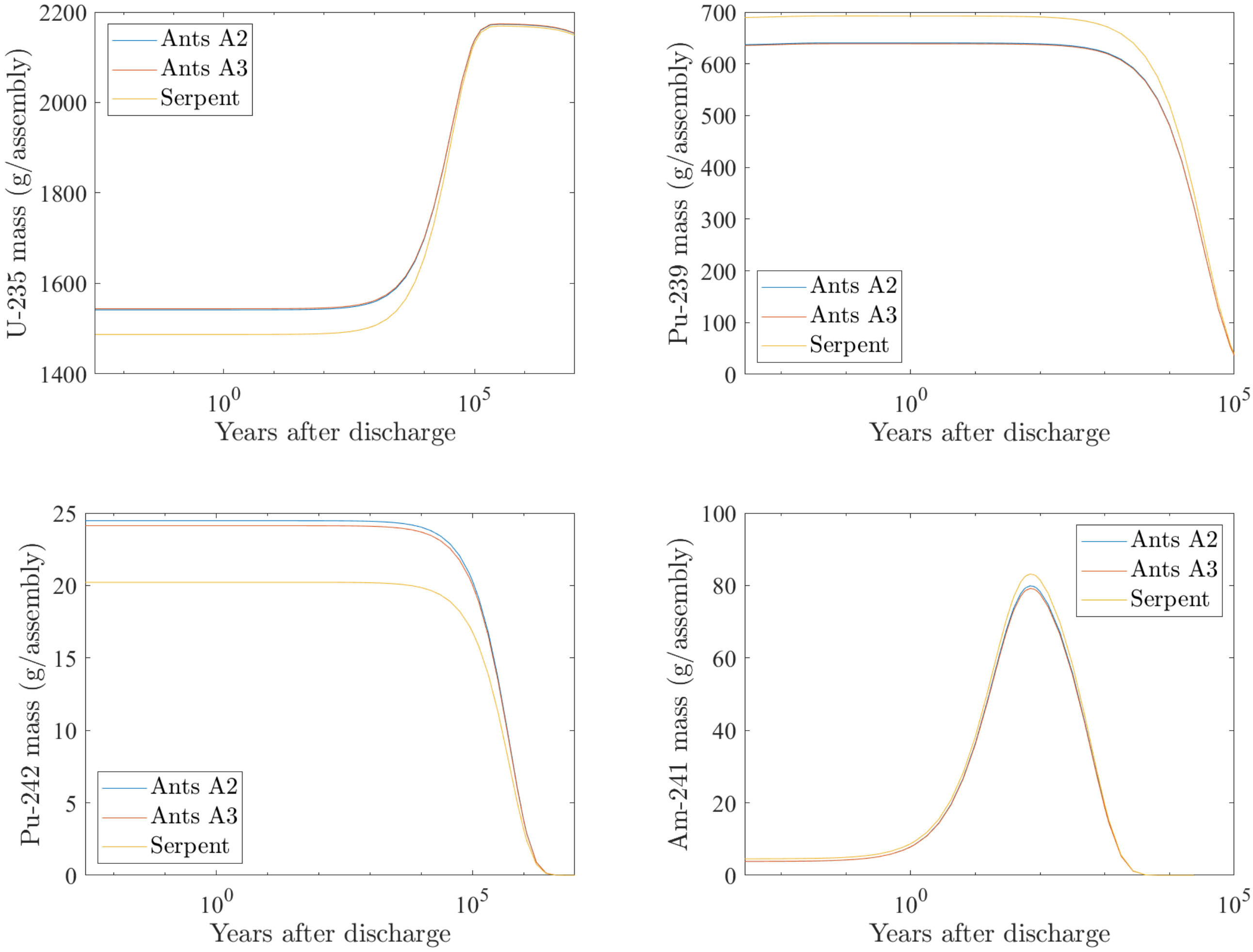

Figure 5. Inventories of U-235, Pu-239, Pu-242 and Am-241 in the spent fuel with 5 % Gd.

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3. Work package 2 (WP2) Identifying future research and development needs for implementation of SMR waste management in Finland

3.1 Identification of possible organisational models for SMR waste management

This chapter discusses generic organisational models for different SMR waste management strategies (centralised, hybrid, local) in Finland including roles, responsibilities, and division of costs between the parties.

3.1.1 Guidelines from current regulations

The effect of Finnish regulations on SMR waste management have been previously discussed in Keto et al. (2023). As updating the Nuclear Energy Act (990/1987) is ongoing while writing this report, changes to the Finnish regulations remain to be analysed during 2025 (a task planned for the final year of the SMRSiMa project). Currently the most relevant regulations from organising the waste management include:

- **Disposal of nuclear waste in Finland**: “Nuclear waste generated in connection with or as a result of use of nuclear energy in Finland shall be handled, stored and permanently disposed of in Finland” (Section **6a**). This does not include small amounts of waste that that have been generated in research purposes, or waste generated in a research reactor, or “minor quantities of radioactive material which is delivered to another country for treatment in the appropriate manner.”
- **Prohibition to import nuclear waste**. Nuclear waste generated outside Finland cannot be handled, stored or disposed in Finland (Section **6b**). This is not applicable to “small amounts of nuclear waste which will be, or have been, delivered to Finland for research purposes” or “nuclear waste of unknown origin referred in section 80, subsection 1”.
- **Waste management obligation and costs**: “License holder whose operations generate or have generated nuclear waste (party with a waste management obligation, *jätehuoltovelvollinen in Finnish*) shall be responsible for all nuclear waste management measures and their appropriate preparation, as well as for their costs (waste management obligation, *huolehtimisvelvollisuus*), section **9**”. The basis on which the waste management obligation shall be implemented is determined by Ministry of Economic Affairs and Employment (section **28**).
- **Transfer of waste management obligation**: “When a nuclear facility, a mine intended for the production of uranium or thorium, a milling facility, or nuclear waste is transferred to another party, the Ministry of Economic Affairs and Employment may, on request, transfer the management obligation (*huolehtimisvelvollisuus*) to the transferee in part or in full if the transfer of the obligation does not endanger the implementation of the nuclear waste management*”, section **30**.* As stated in the Nuclear Energy Degree (161/1988) section 81, the waste producer and transferee must apply for the transfer of waste management obligation together and the **transferee must possess an operating license** granted by the government. In addition, separate permission is needed from STUK for transference of the waste.
- **Financial provision obligation** (section **36**). In general, the party with the waste management obligation shall fulfil the financial provision obligation by payment for each calendar year to National Nuclear Waste Management Fund (Nuclear Energy Act, Section 36 Financial provision measures). The fund is used to ensure that the government has sufficient funds and expertise to arrange nuclear waste management under all circumstances. *Note that does not mean that the costs of the disposal would be covered from this fund at the time of the management operations, and the full responsibility of the costs lies with License holder whose operations have generated the waste as defined in Section 9.* There is also collateral security that the license holder needs to furnish the state as precaution against insolvency (defined in chapter 7 of the Nuclear Energy Act).

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- **Expiration of the waste management obligation** (section **33**). This can take place transfer of the waste management obligation, when the nuclear waste has been transferred outside Finland's jurisdiction (see section 6a) or after disposal of the waste. After disposal, the responsibility of the waste is transferred to the State (section **34**).

As stated in Keto et al. (2023), it is in the interest of all parties (nuclear waste producers, waste management organizations, regulator, government, and the public) that **a transfer of the waste management obligation is done under mutual understanding.** This means that utilizing sections 29 (mandatory waste management cooperation) or 31 (transfer of the nuclear waste to the State) is not seen as a good practice and should be used as a last resort for implementing nuclear waste management.

- The spent fuel from VTT's research reactor FiR 1 has been returned to US at the end of 2020 according to Nuclear Energy Act (990/1987) section 6a § (MEAE 2022b). The decommissioning waste (LILW) from the research reactor Fir1 is the first example where the waste management obligation has been transferred from, in this case, VTT to Fortum Power and Heat Oyj. Licenses were granted by TEM during 2023 both for transfer of the waste management obligation (to Fortum Power and Heat Oy) and for handling, storage and disposal of the waste in Loviisa (to Fortum Power and Heat Oy) based on the Nuclear Energy Act, section 20 § (TEM 2023).
- Operating waste that will be generated by Posiva oy as a consequence of spent nuclear fuel encapsulation and final disposal will be transferred to TVO (MEAE 2024).

3.1.2 Organisational/business models in line with the current legislation

Organisational or business models that are aligned with the current legislation include:

- **License holder model**. Management, storage, handling and disposal of nuclear waste is carried out by the license holder . This case is applied in Finland with local disposal of LILW at the NPP sites directly by the party with the waste management obligation. It is important that this party has the license for disposal and that the organization has sufficient knowhow for disposal.
- **Ownership of a waste management company model**: This model can be applied with or without transfer of waste management obligation (huolehtimisvelvollisuus) to a company owned by the party/parties with the waste management obligation. TVO and Fortums's ownership of Posiva is an example of this model.
- **Service model** including transfer of the waste management obligation to another party. The FiR 1 reactor case is an example of this model. In this case, VTT and Fortum Power and Heat Oy eeded to make a financial agreement. In addition, licenses were needed for handling, storage and disposal of the waste by the service producer. The transfer of the waste management obligation required a decision by TEM.

3.1.3 Organisational/business models not in line with the current legislation

Most of these alternatives mentioned below have been discussed as alternative ways to manage SMR waste, but they are not currently in line with current legislation.

- **Leasing of fuel model**. Leasing of fresh fuel would imply that the waste management obligation would belong to the party leasing the fuel (lessor) and not with the party (lessee) temporarily using the fuel and effectively generating the waste. The lessor would own and take back the spent fuel after use, possibly re-process or treat it depending on the reactor type considered and take care of the interim storage and disposal of the fuel after processing. This model can be further considered along two lines:

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- **a) Fuel Leasing from a Finnish company:** This alternative would be aligned with the Nuclear Energy Act: 6a (assuming handling, storage and disposal in Finland), but conflicts with 9 (party generating the waste has the waste management obligation).
- **b) Fuel Leasing from a foreign company:** This alternative is not aligned with the Nuclear Energy Act: 6a (assuming handling, storage and disposal is not managed in Finland) or with 9 (party generating the waste has the waste management obligation). Council Directive 2011/70 states that radioactive waste shall be disposed of in the member state in which it was generated (Article 4), unless there is an agreement in force between Member States or a Member State or a third country.

- **National disposal facility**. A national disposal facility would be funded by the state of Finland (public funding from the government budget) and/or from the funds (financial provision obligation or similar) collected from the producer of the waste (party with the waste management obligation). Conflicts possibly with Nuclear Energy Act: 9 (party generating the waste has the waste management obligation), and 36 (financial provision obligation).
- **Shared disposal facility.** Interim storage and disposal in a common disposal facility for several countries. The costs of storage and disposal would be covered by the users of the facility. The location of the facility could be either in Finland (conflicts with Nuclear Energy Act, section 6b on import) or outside Finland in another EU country (conflicts with Nuclear Energy Act: 6a on export. Either option would require a change in Finnish law. The safe execution would possibly require more regulations to ensure that safe disposal through e.g. through insurance, auditing and other practices. Council Directive 2011/70 states that this option would also require agreements between the Member States concerned.
- **Export for reprocessing.** Large-scale export (no minor quantities) to reprocess SNF could generate funds for disposal of the returned wastes. This conflicts with the Nuclear Energy Act, 6a (export). In theory this approach could be applicable for many different organizational models.

3.2 Pre-study on regulatory safety oversight of organizational, management and leadership aspects in SMR lifecycles

This chapter presents the results from the pre-study aimed at identifying potential challenges and pitfalls in regulatory safety oversight from organizational, management, and leadership perspectives throughout the lifecycle of SMRs. The chapter consists of a short review of existing public material and descriptions of four scenarios of the “desired futures of SMRs in Finland” based on interviews with Finnish nuclear experts and reflective discussions with representatives of STUK (on 11.11.2024 and 20.1.2025) and the OECD NEA Working Group on Human and Organizational Factors (WGHOF) SMRs task group on 22.1.2025. Finally, the chapter ends with limitations and conclusions.

3.2.1 Review of existing public material on organizing for SMRs

Global efforts for clean energy and other external factors are accelerating investments and SMR deployment. Recent media headlines emphasised a strong demand for nuclear (both advanced and conventional) as the major technology companies like Microsoft, Amazon and Google have all publicly made commitments to procure nuclear energy (Oblick 2024, Stevens 2024 and Warren 2024). In addition, the World Economic Forum (2024) published a framework for accelerating advanced nuclear and SMR deployment that serves as a tool to align stakeholders on key actions within certain priority areas. Furthermore, governments are increasingly involved by providing funding for research and development for SMR deployment (e.g., Natural Resources Canada 2024). According to these initiatives key human and organizational factors (HOF) topics include the development of nuclear-qualified personnel, the construction and commissioning of new nuclear projects and project delivery models, and the readiness of domestic manufacturing and supply chains, all of which are essential for building the required human resources and infrastructure. From the SMR organising perspective, the focus seems to be on the

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development of the innovative project delivery models, and how the developers manage risks and incentivize efficient deployment. Both the Integrated Project Delivery (IPD) approach, which is adopted, for example, by Ontario Power Generation for its Darlington SMR project, and prime contract structure, used for example in the construction of the Barakah NPP, United Arab Emirates' first nuclear power station, which achieved a 40 % schedule improvement from the first to fourth unit (WEF, 2024), are being considered for SMR projects.

The possible pitfalls of fierce international market competition and aggressive project schedules should be noted as well. Lessons learned from the Boeing 737 MAX incidents highlight the potential latent safety implications of competitive international pressures. These include regulatory oversight issues (e.g., lack of international coordination on safety standards, inconsistent standards across different authorities, delegation of authority) and corporate decisions (e.g., poor internal communication of safety concerns, expedited development and certification, prioritizing profit margins over comprehensive safety evaluations). Such factors should be carefully considered to avoid similar pitfalls in the nuclear industry (Viitanen et.al., 2024).

Attention on the role of human and organisational factors in international discussions on SMRs is still rather limited. "Safety culture" is mentioned just once in the recent IAEA publication "Small Modular Reactors: Advances in SMR Developments" (2024a) and only in the context of engaging with the IAEA's expert missions and peer reviews, while terms such as "leadership" or "safety management" are not mentioned in this publication at all. IAEA's INSAG-28 (2024b) does emphasise the role of human aspects and safety culture as part of defence in depth for SMRs, as for example describing the efficient cooperation and clear division of responsibilities as essential elements of strong safety culture on all applications of SMRs.

Research conducted by the UK's Office for Nuclear Regulation (ONR) (Screeton 2024) into identifying the **human and organizational factors challenges in SMR/AMR deployment**, identified the following areas where further work may be required to fully understand the benefits, risk implications, and what relevant good practice may look like in these areas:

- New lean organizational design models, that may rely on the supply chain for delivery of significant parts of the technical analysis, as well as for SSC manufacture and plant build. Some new vendor organizations are constrained by a lack of revenue during the long design phase, which requires careful balancing of the size of the technical organization. This places significant reliance on the effectiveness of intelligent customer roles to ensure quality in the supply chain.
- Enhancements to the technical competency in regulatory regimes, vendor and operator organizations, as well as possible necessary changes to law and policy. Evolutionary designs benefit from an established knowledge base within stakeholder organizations, as well as proven legal and policy frameworks. Changes to stakeholder skill and knowledge bases, as well as changes to legal and policy frameworks, may be required for some, as yet, un-proven reactor technologies.
- Development of some SMR/AMR enabling technologies has outpaced the understanding on how to best optimize them for human interaction. In design features such as, inherent and passive safety, advanced automation, or AI, research is required to better understand the socio-technical implications of failures. Additionally, it is important to understand what future safety cases need to look like to demonstrate adequate safety, security, and safeguards.
- The need to move away from traditional 'safety cases' to those that integrate all functions, e.g., operational, safety, security, safeguards, and environmental requirements. In these cases, functions are considered holistically to ensure a design that is better optimized.

SMRs are designed to operate with fewer staff for operation and maintenance, and vendors must prove to licensing bodies that safety won't be compromised. Autonomous control, AI, and digital twin technologies are crucial, requiring innovative hardware and software. Simplified hardware and supportive software can reduce individual workload, while digital twins predict system degradation to optimize maintenance and component replacement. (Lee, 2024)

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Blackett (2024a and 2024b) highlights several assumptions about SMRs, such as their high level of automation and potential for autonomous, remote multi-unit operations and minimal staffing and cautions that to truly understand how SMRs will be operated and the associated risks, it is essential to critically examine these assumptions to distinguish between fact and hype.

3.2.2 "Desired futures of SMRs in Finland"- scenarios

The changing regulatory landscape, business potential, and new technology implementation are driving forces behind the focus on the near future, removing barriers, and increasing possibilities for using new technologies. Collecting narratives about desired future of organizing aims to spark imagination and long-term perspectives on what is wanted, needed, and how this could be achieved. The goal of this pre-study was to start uncovering the assumptions and possibilities for desired SMR organizing in the future and trigger debates about the future and to ponder what is possible. The interview method incorporates elements of future-oriented speculative design, which seeks to stimulate debate and critical reflection on the implications of emerging technologies and the links to safety, thereby aiding in our preparation for potential futures.

Interviewees were asked to freely imagine a situation in Finland in the 2040s - 2050s, when several SMRs are already serving the needs of industries and cities. Key questions included:

- How would these plants look and operate?
- How would the safety and quality of operations be ensured?
- How was such future achieved and what were the key success factors?

Four experts were interviewed, including senior experts, predominantly male with nuclear backgrounds, active in the nuclear and SMR fields. They represented different organizations, including one research institution and three private companies. Each interview lasted one hour and was conducted during November-December 2024. The interviews were conducted in English online and recorded as transcripts with the consent of the persons interviewed. Scenarios with key features were summarized based on the recordings. These scenarios were then sent to the interviewees for review and confirmation. The organizing models were visualized based on the narratives and the scenario descriptions.

3.2.2.1 Scenario A

Scenario A highlights a strong **international nuclear vendor as the license holder**, disrupting the Finnish market by providing heat and power services to local energy companies and industrial end-users. The service provider has a **central office** that handles procurement, maintenance, planning, and other centralized tasks, and establishes the **main operator organization** overseeing daily operations, maintenance, and emergency preparedness, with remote operation capabilities and on-site emergency control rooms. **Multiple decentralized plants** operate on a demand basis in close cooperation with end-users. **Safety and oversight** are stringent, with updated internal and external measures for new technologies. Inherent SMR safety features and robust cybersecurity are emphasized. Regulations enable licensing ten times faster. Operators manage **waste processing**, treatment, and disposal. Owners ensure a clear disposal strategy, using existing or new repositories. International nuclear waste disposal offers a business opportunity. **Success factors** include revised regulations for SMRs, high public acceptance due to trust and transparency, and experienced organizations ensuring safe, sustainable operations. This scenario is depicted in Figure 6 and its organising model in Figure 7.

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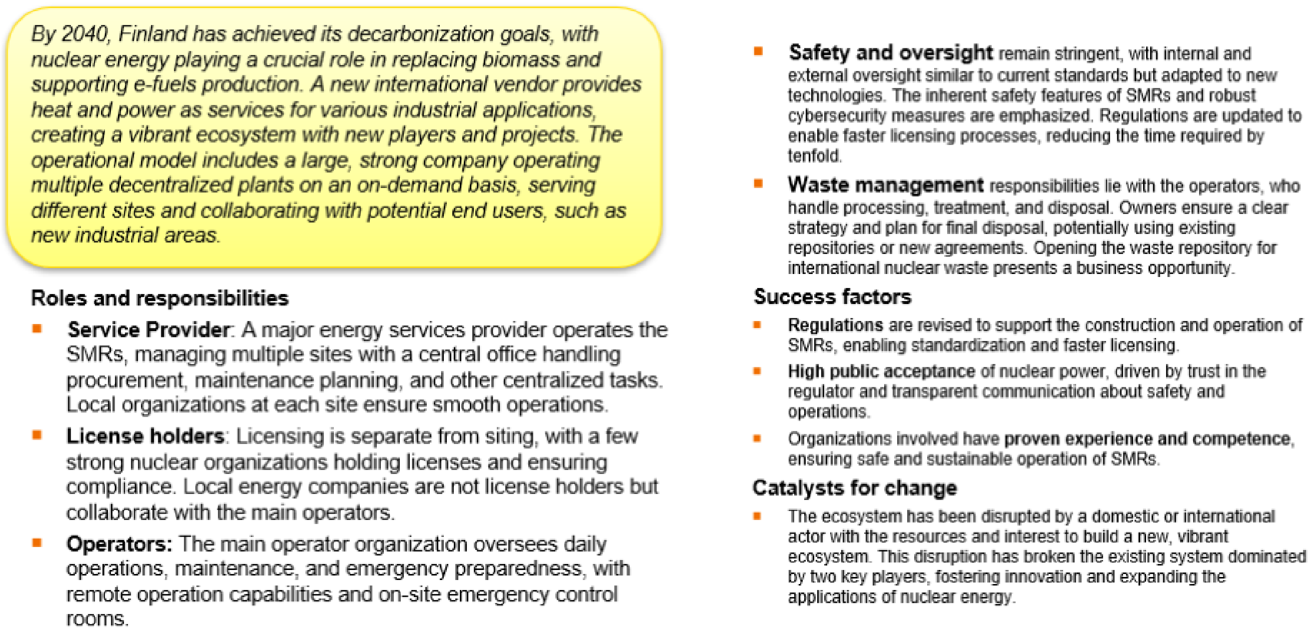

By 2040, Finland has achieved its decarbonization goals, with nuclear energy playing a crucial role in replacing biomass and supporting e-fuels production. A new international vendor provides heat and power as services for various industrial applications, creating a vibrant ecosystem with new players and projects. The operational model includes a large, strong company operating multiple decentralized plants on an on-demand basis, serving different sites and collaborating with potential end users, such as new industrial areas.

Roles and responsibilities

- **Service Provider**: A major energy services provider operates the SMRs, managing multiple sites with a central office handling procurement, maintenance planning, and other centralized tasks. Local organizations at each site ensure smooth operations.
- **License holders**: Licensing is separate from siting, with a few strong nuclear organizations holding licenses and ensuring compliance. Local energy companies are not license holders but collaborate with the main operators.
- **Operators:** The main operator organization oversees daily operations, maintenance, and emergency preparedness, with remote operation capabilities and on-site emergency control rooms.
- **Safety and oversight** remain stringent, with internal and external oversight similar to current standards but adapted to new technologies. The inherent safety features of SMRs and robust cybersecurity measures are emphasized. Regulations are updated to enable faster licensing processes, reducing the time required by tenfold.
- **Waste management** responsibilities lie with the operators, who handle processing, treatment, and disposal. Owners ensure a clear strategy and plan for final disposal, potentially using existing repositories or new agreements. Opening the waste repository for international nuclear waste presents a business opportunity.

Success factors

- **Regulations** are revised to support the construction and operation of SMRs, enabling standardization and faster licensing.
- **High public acceptance** of nuclear power, driven by trust in the regulator and transparent communication about safety and operations.
- Organizations involved have **proven experience and competence**, ensuring safe and sustainable operation of SMRs.

Catalysts for change

- The ecosystem has been disrupted by a domestic or international actor with the resources and interest to build a new, vibrant ecosystem. This disruption has broken the existing system dominated by two key players, fostering innovation and expanding the applications of nuclear energy.

Figure 6. Scenario A.

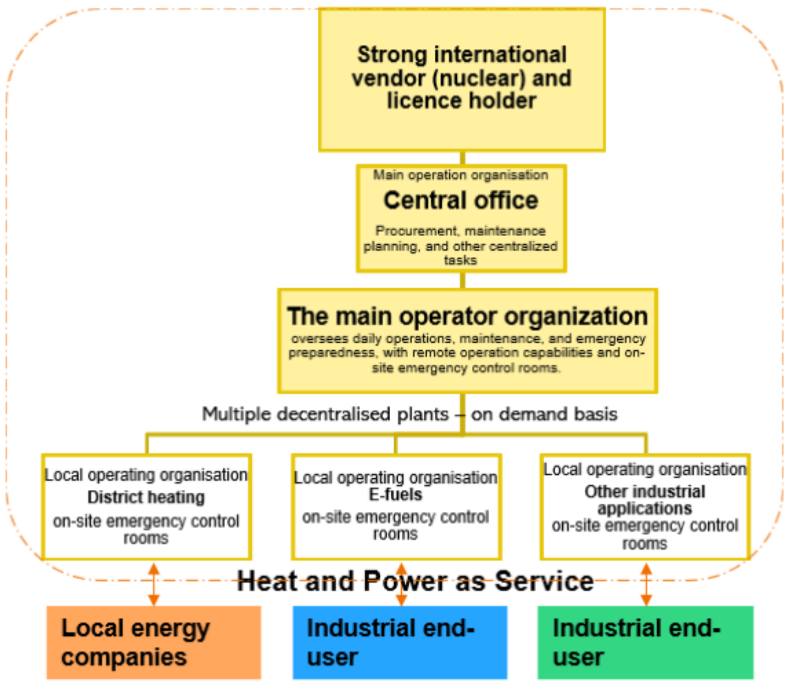

Figure 7. Scenario A - Organising model.

3.2.2.2 Scenario B

Scenario B envisions Finland in a pioneering role for SMRs, with high public acceptance of nuclear use. SMRs are business-driven, with multiple units operating in Helsinki and across Finland. **The license holder** responsible for safety may differ from the operator, allowing smaller utilities to leverage the expertise of dedicated operators without extensive in-house capabilities. **The main operator organization** manages remote operations of multiple units with hundreds of specialized nuclear experts for overall management, maintenance, and support. They solve design problems locally, maintain a lean structure with low hierarchy, and operate in English. **Safety and oversight** follow a more adaptable regulatory

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approach, focusing on achieving safety standards rather than rigid rules. Regulations allow flexible plant placement and remote operations, provided safety levels are maintained, and mechanisms are in place to manage incidents and protect the population. Operators manage **waste processing**, treatment, and disposal, while owners ensure a clear disposal strategy, viewing spent nuclear fuel as a resource to be reprocessed and significantly reducing disposal needs. **Success factors** include revised regulations for SMRs, high public acceptance due to trust and transparency, and experienced organizations ensuring safe, sustainable operations. Scenario B is presented in Figure 8 and its organising model in Figure 9.

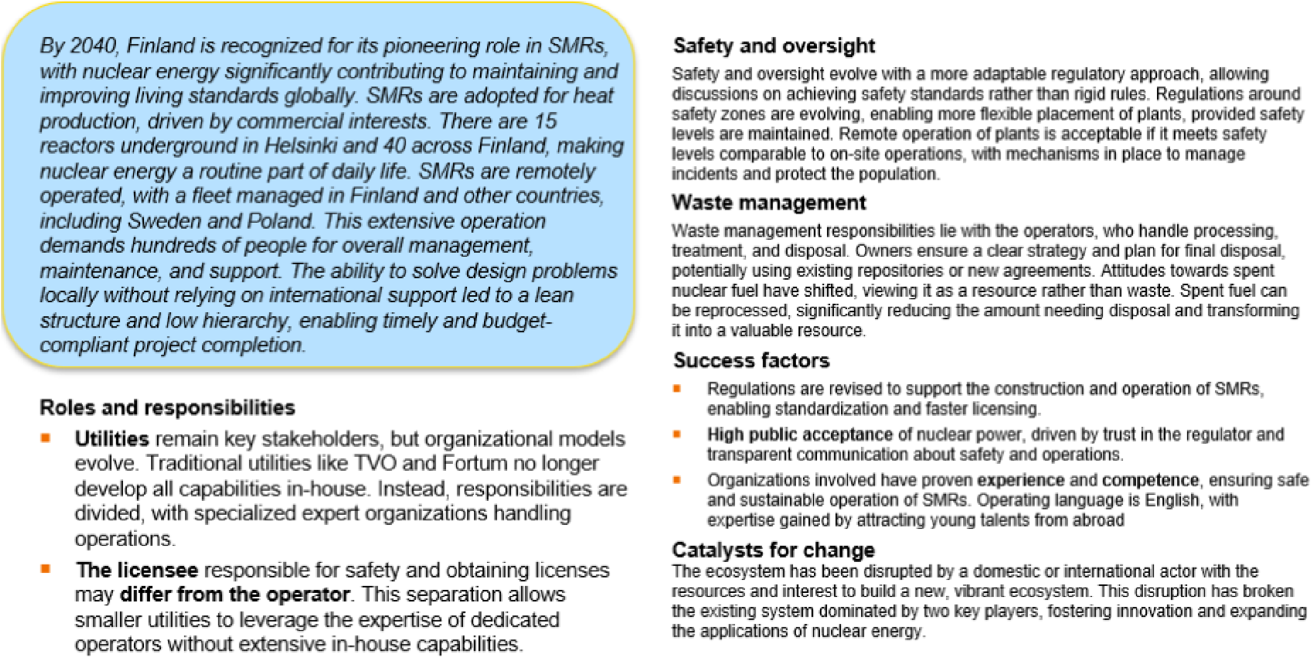

Figure 8. Scenario B.

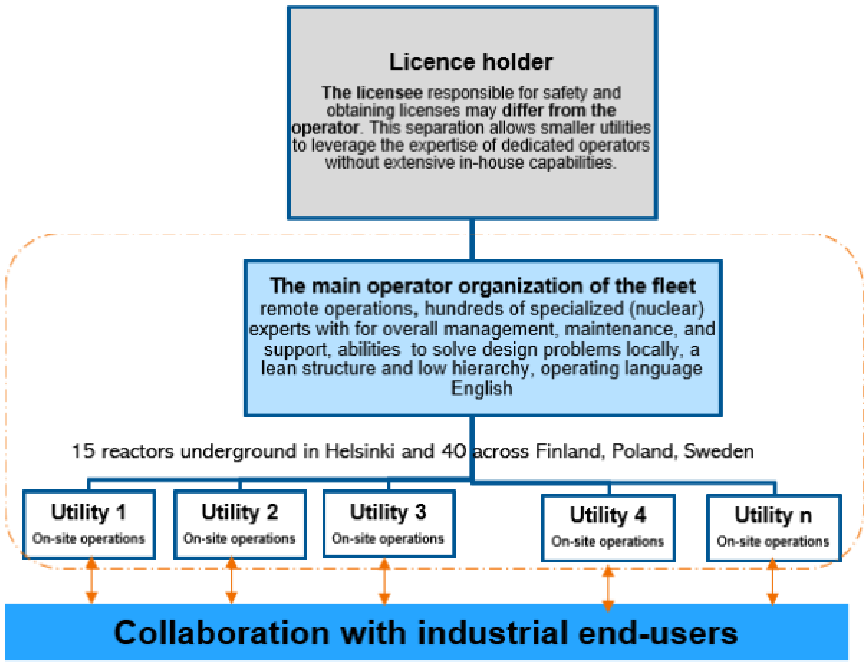

Figure 9. Scenario B - Organising model.

3.2.2.3 Scenario C

Scenario C envisions the future in a more cautious way, as there have been obstacles to SMR deployment due to the growing use of wind and solar energy and unchanged stringent nuclear safety requirements. There are a few operational SMRs owned by local energy companies and licensed by international vendor. **The license holder** is responsible for safety, and the operator may differ, allowing smaller utilities to operate without extensive in-house capabilities. **The main operator** has a control room managing multiple SMRs with advanced safety design and automated safety functions ensuring safe shutdowns. SMRs do not require constant staffing, although qualified staff are within short distance to handle any issues. **Safety and oversight** remain stringent, with STUK maintaining high standards and evolving regulations. New challenges like EMPs, terrorism, and human error emphasize the need to protect network connections and overall electricity systems. **Nuclear waste management** will require multiple storage sites, with Posiva's Onkalo facility handling some waste and additional facilities managed across Finland to ensure safe and secure storage. **Success factors** include risk-taking international investors, an adaptable and competent project team, harmonized European standards for SMRs, and ensuring STUK's independence by involving more independent experts to enhance public trust and regulatory effectiveness. Scenario C and its organising model are presented in Figures 10 and 11, respectively.

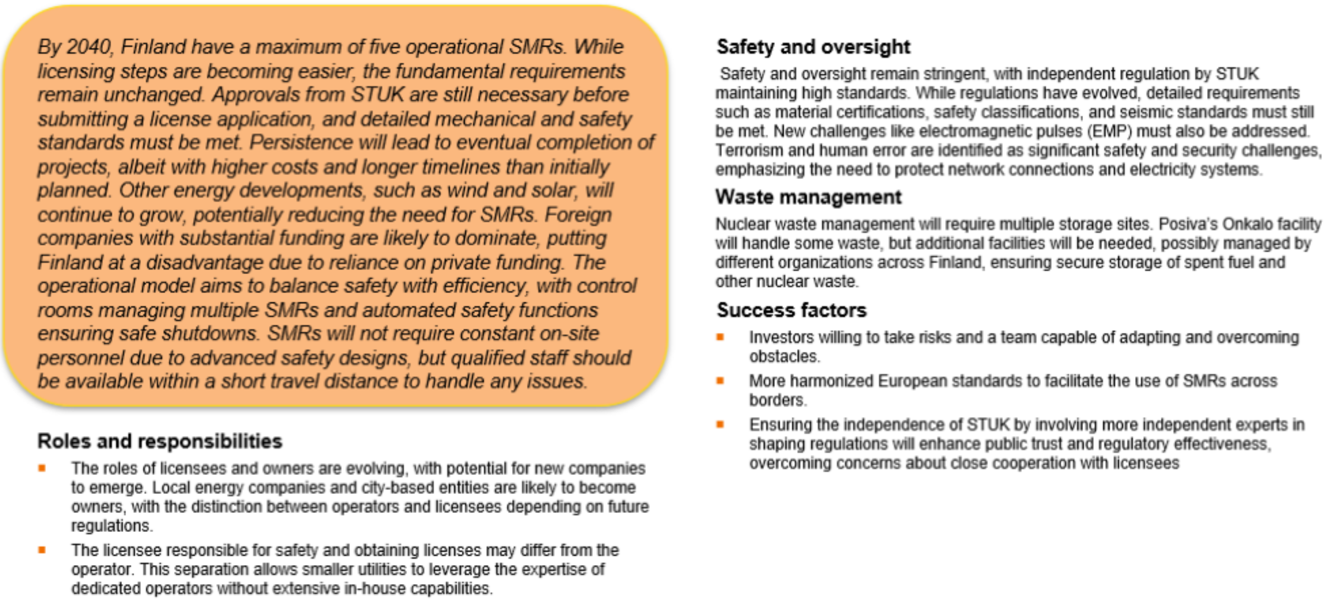

Figure 10. Scenario C.

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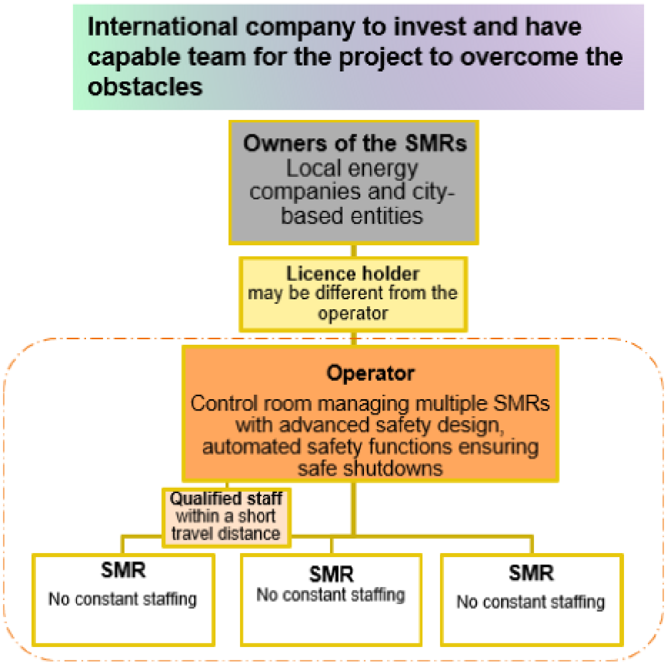

Figure 11. Scenario C – Organising model.

3.2.2.4 Scenario D

Scenario D describes the future of SMRs by building on the extensive experience of current nuclear power plants and the competence development of all stakeholders. The vision is based on SMRs managed through Power Purchase Agreements and turnkey contracts, emphasizing standardization for cost-effective deployment. SMRs could be **owned** by a wide range of organizations or coalitions, including smaller regional energy companies and various industry players. **The license holder** responsibilities will remain with the owners, ensuring compliance with regulatory requirements and overall safety responsibility, and ensuring the capability and competence to supervise the operation and maintenance (O&M) organization. The license holder forms an **O&M organization** to fulfil these obligations. Daily operations and maintenance planning will involve fewer operators, with the operator handling emergency preparedness and response, and possible remote operations. An SMR site with multiple units providing district or industrial heat will have 10–20 staff. **Safety and oversight** for SMRs involve clearly defining the license holder's roles and responsibilities within legislation and regulations, ensuring they can supervise the O&M organization. Safeguards address both physical and cybersecurity threats, emphasizing inherent safety features and focusing on actual safety outcomes. Operators are responsible for **SMR waste management**, while owners must secure a final disposal strategy before operations begin. **Success factors** include harmonizing international regulatory and licensing requirements for standardized reactor designs and gaining public acceptance through clear communication and trust in the regulator. Organizations must demonstrate their capability to operate SMRs safely and sustainably, building trust through proven expertise. The summary and organising model for scenario D are presented in Figures 12 and 13.

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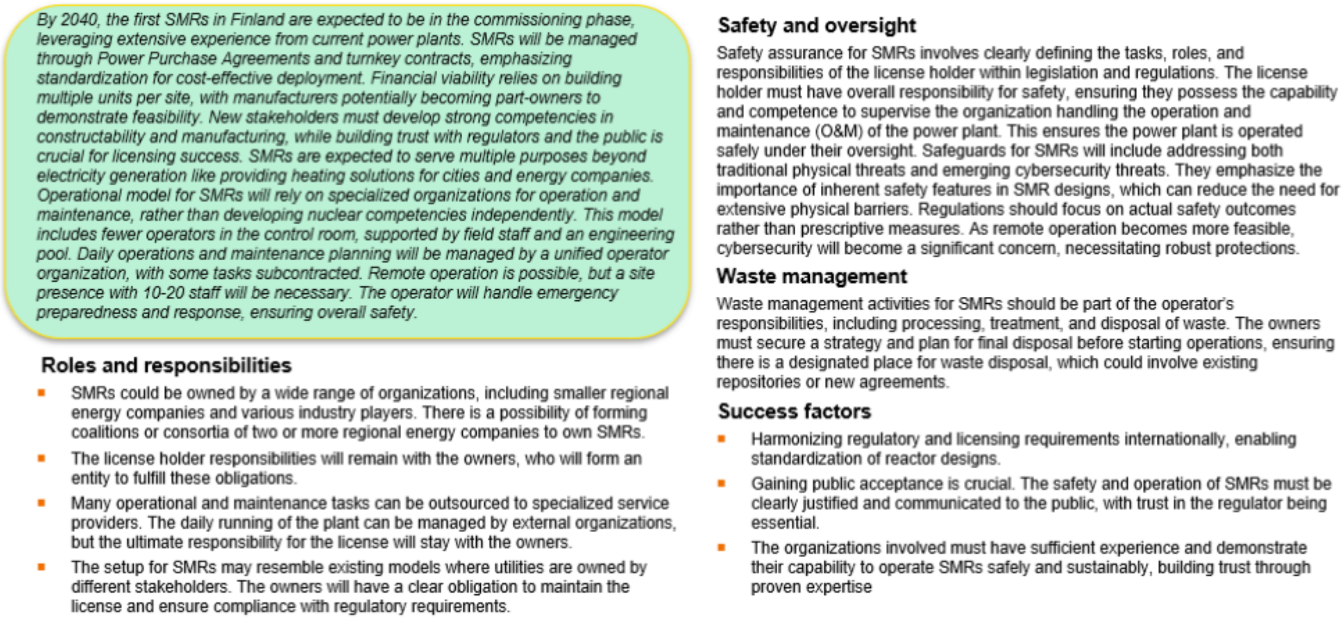

By 2040, the first SMRs in Finland are expected to be in the commissioning phase, leveraging extensive experience from current power plants. SMRs will be managed through Power Purchase Agreements and turnkey contracts, emphasizing standardization for cost-effective deployment. Financial viability relies on building multiple units per site, with manufacturers potentially becoming part-owners to demonstrate feasibility. New stakeholders must develop strong competencies in constructability and manufacturing, while building trust with regulators and the public is crucial for licensing success. SMRs are expected to serve multiple purposes beyond electricity generation like providing heating solutions for cities and energy companies. Operational model for SMRs will rely on specialized organizations for operation and maintenance, rather than developing nuclear competencies independently. This model includes fewer operators in the control room, supported by field staff and an engineering pool. Daily operations and maintenance planning will be managed by a unified operator organization, with some tasks subcontracted. Remote operation is possible, but a site presence with 10-20 staff will be necessary. The operator will handle emergency preparedness and response, ensuring overall safety.

Roles and responsibilities

- SMRs could be owned by a wide range of organizations, including smaller regional energy companies and various industry players. There is a possibility of forming coalitions or consortia of two or more regional energy companies to own SMRs.
- The license holder responsibilities will remain with the owners, who will form an entity to fulfill these obligations.
- Many operational and maintenance tasks can be outsourced to specialized service providers. The daily running of the plant can be managed by external organizations, but the ultimate responsibility for the license will stay with the owners.
- The setup for SMRs may resemble existing models where utilities are owned by different stakeholders. The owners will have a clear obligation to maintain the license and ensure compliance with regulatory requirements.

Safety and oversight

Safety assurance for SMRs involves clearly defining the tasks, roles, and responsibilities of the license holder within legislation and regulations. The license holder must have overall responsibility for safety, ensuring they possess the capability and competence to supervise the organization handling the operation and maintenance (O&M) of the power plant. This ensures the power plant is operated safely under their oversight. Safeguards for SMRs will include addressing both traditional physical threats and emerging cybersecurity threats. They emphasize the importance of inherent safety features in SMR designs, which can reduce the need for extensive physical barriers. Regulations should focus on actual safety outcomes rather than prescriptive measures. As remote operation becomes more feasible, cybersecurity will become a significant concern, necessitating robust protections.

Waste management

Waste management activities for SMRs should be part of the operator's responsibilities, including processing, treatment, and disposal of waste. The owners must secure a strategy and plan for final disposal before starting operations, ensuring there is a designated place for waste disposal, which could involve existing repositories or new agreements.

Success factors

- Harmonizing regulatory and licensing requirements internationally, enabling standardization of reactor designs.
- Gaining public acceptance is crucial. The safety and operation of SMRs must be clearly justified and communicated to the public, with trust in the regulator being essential.
- The organizations involved must have sufficient experience and demonstrate their capability to operate SMRs safely and sustainably, building trust through proven expertise

Figure 12. Scenario D.

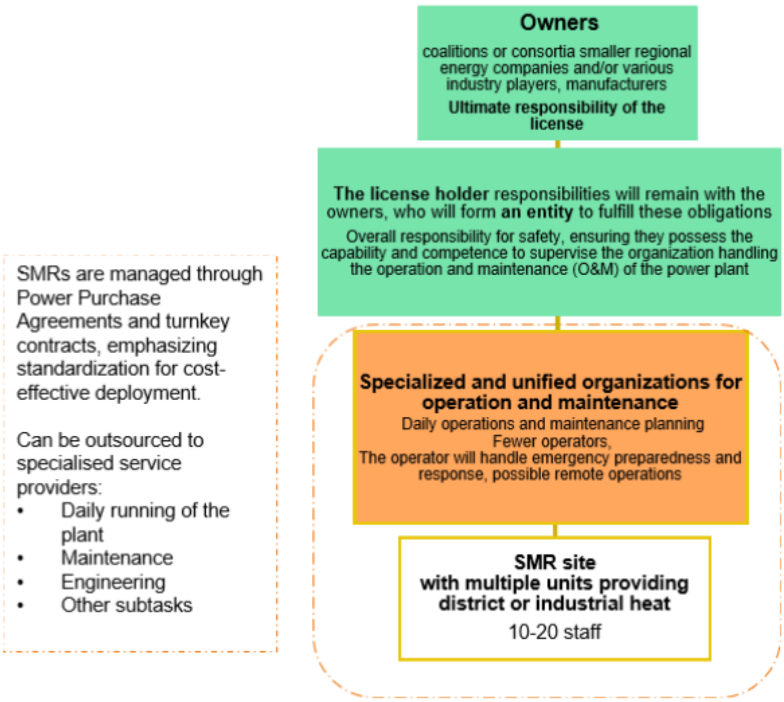

Figure 13. Scenario D – Organising model.

3.2.2.5 Reflecting on the scenarios

The narratives of desired futures were differently described, highlighting different aspects and mainly quite general. While discussing desired futures, participants expressed various conditions and uncertainties, and some found it challenging to stay within the interview theme of 'desired future." All scenarios involve multiple purposes for SMRs beyond electricity production and some form of decentralized operational model for managing nuclear energy production and distribution. Relationships between license holders, operators, and end-users are considered essential, and each scenario highlighted this configuration differently. Each scenario highlights the need for regulatory approvals and adherence to safety standards,

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although the specifics vary. Perceived success factors were similar and included harmonizing regulatory and licensing requirements, public acceptance, and specialized nuclear competencies.

Based on the discussion with representatives of STUK, the scenarios were considered general but provide interesting and rich perspectives on the possible futures of SMRs. A common assumption across all scenarios is the adoption of a specific type of SMR design—small reactors with inherent safety features. All the scenarios also distinguish between the roles of the license holder and the operator to a different organisation which sparked discussions around the topic of **the interactions and roles and responsibilities between the key stakeholders**.

Furthermore, there seems to be an assumption in the scenarios that the license holder can be a small organization relying on a competent operator organization. The license holder's role seems to be seen as supervising operations and act as an independent supervisor of the operators. It was highlighted that the **specific safety responsibilities of utilities and their interaction with the license holder need to be clearly defined** also in the future. Differentiating the operator from the license holder might bring challenges, especially in situations requiring immediate safety-related decisions. Both roles require expertise, and **expectations for each need to be clearly defined**. The **license holder must be able to influence safety-related decision-making in practice**, not just on paper. Some scenarios suggest the involvement of a strong international vendor as license holder. However, it is still unclear if the vendor could also hold the license or if the license holder serves multiple vendors. Clarifying this relationship in the future is important for understanding the operational dynamics and safety implications. Regardless of the risks and type of reactor, the licensee must ensure that requirements are fulfilled and demonstrate the capability to be an intelligent customer if outsourcing activities. The licensee must demonstrate that their arrangements are safe.

STUK representatives also suggested that further research should aim at investigating indicators and methods for licensees to demonstrate the safety of their organizational and operational models, especially if multiple licensees exist in the future. It is important to study best practices and requirements for organizations to justify their structure and resourcing, particularly when making changes. Examining how licensees can provide clear explanations of their activities and functions, avoiding complexity and ensuring transparency, is also necessary. In addition, exploring the differences between becoming a licensee or an operator, including the competences and expectations for each role, would provide valuable insights.

Similar reflections were drawn also from the discussion with the international OECD NEA WGHOF member representatives: the overall perception was that this future-oriented research method seemed powerful in producing very rich and thought-provoking insights. Some suggested topics for further studies included elaborating the links between organizational design and safety management, the need for new competences development, clarifying the roles and responsibilities between key safety significant stakeholders, the links between technology design choice and organizational models and new security aspects for SMRs.

3.2.3 Limitations

The scenarios described in the report should not be considered as accurate predictions of the future of SMRs in Finland. These scenarios are based on one-hour interviews, which provided limited time for in-depth exploration and comprehensive analysis. Furthermore, the use of less structured questions, while encouraging unrestrained creativity, leads to less consistent data. Consequently, the insights gathered may reflect the immediate perspectives and experiences of the interviewees rather than a thorough examination of possible factors and variables, which may be realized in the future. Moreover, the speculative nature of these scenarios means they are intended to provoke thoughts and dialogue rather than predict outcomes. However, they may serve as powerful discussion forums in terms of pros and cons of different organizational configurations and their safety implications. They are a tool to explore potential futures and stimulate critical thinking, but lack the empirical rigor and validation required for extensive conclusions. Therefore, while these scenarios offer valuable insights and highlight important considerations, they should be interpreted as preliminary and exploratory, rather than definitive forecasts.

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3.2.4 Conclusions

The SMR discussion is mainly focused on technology and economic aspects to ensure successful deployment, with a strong emphasis on the front-end of SMR projects. Human factors researchers are raising concerns, but there is still weak representation of HOF, management, leadership, and organizing aspects in scientific, media, and other publications (one notable exception being IAEA, INSAG-28, 2024). The ‘socio’ from ‘socio-technical systems’ is largely missing from major publications, posing a risk that these aspects will be considered late or insufficiently. Several potential challenges and pitfalls need to be considered in the regulatory oversight of organizational, management, and leadership aspects throughout the SMR lifecycle.

The desired future of SMRs scenarios highlight assumptions related to the emergence of future SMRs, including harmonized regulation and standardization of design with inherent safety features, and operating organizations as fleets of remotely operated units with or without onsite personnel. There is a shared perceptions that safety must be ensured, and public acceptance is necessary. The scenarios emphasize the division of roles and responsibilities between the license holder and main operations, which may present challenges if not considered in advance. Engaging with nuclear experts to envision, share and discuss desired futures is one way to remain prepared and vigilant amidst the current dynamic environment, while also being conscious of the unintended consequences of changes to maintain a high level of safety and safety culture.

Currently, the nuclear industry emphasizes understanding safety as a complex and systemic phenomenon as part of its safety culture. However, if future SMR designs feature simplified hardware, fewer personnel, and streamlined licensing processes, there may be a tendency to oversimplify interpretations of events and interactions between human, organizational, and technical factors, or human-automation interactions. Higher levels of automation can actually increase cognitive complexity. Additionally, organizational complexity in SMRs, including supply chains, multiple organizational/management system boundaries, and distributed roles and responsibilities, must be considered.

4. Conclusions

The first objective of this project was to investigate the effect of the small core size on SMR SNF properties. The LDR lite small core inventory calculations with the Serpent – Ants sequence were performed and repeated over a sufficient number of cycles that equilibrium was achieved, i.e., the discharged fuel assemblies practically do not differ between consecutive cycles. The output suggested clearly that the axial burnup profile is far from the relatively flat one typically observed for large PWR fuel. When considering the decay heat generation by a single fuel assembly, the axial variation did not cause major deviations with respect to the Serpent 2D assembly calculation to the assembly average burnup. Similar observations apply for total activity, although this was outside the scope of the results for this study. However, one should consider that the segment with the highest activity of the spent fuel assembly is higher than the average burnup would suggest, which may – at least theoretically – have an impact on shielding requirements. Additionally, some differences in nuclide compositions were detected such that they may have an impact on spent fuel reactivity. In order to properly determine the impact, transport calculations will be needed for spent fuel at sufficient number of points in time, which will be left for future activities. Generally, the axial profile shape is at least partly explained by the active use of control rods, which would be more flat even for SMRs, if they are boron-controlled similar to current PWRs.

Although an important aspect of spent fuel inventories, mobile nuclides were not discussed in this work. The minute concentrations of N-14 and Cl-35 impurities causing the C-14 and Cl-36 inventories into fuel and cladding were not included in the Serpent input for the group constant generation. In order to add these nuclides into the inventory calculations with Ants, the group constants have to be re-calculated, which is a computationally heavy task. Furthermore, it will need some testing to verify that the computing chain treats them correctly.

The second objective of this report was to study the possible organisational models for SMR waste management. Nuclear waste generated in Finland shall be disposed permanently in Finland following the regulatory framework laid out in the Nuclear Energy Act (990/1987). The licence holder generating the waste is the party with the waste management obligation responsible also for the costs of the management. The organisational models already in use and compatible with the current regulations are that a) the licence holder manages and disposes the nuclear waste (applied in practice for LILW), b) the organisation/organisations own a company that takes care of the waste management in practice (Posiva case) or c) a service model where a third party takes care of the management (e.g., interim storage and disposal) through transfer of the waste management obligation (e.g., Fir1 reactor decommissioning LILW disposed by Fortum Power and Heat Oy). In addition, alternative organisational models that are not in line with the current regulation were identified including fuel leasing I (either Finnish or international company) where the lessor takes care of the final disposal in a national disposal facility or a repository shared with other countries. Large scale export for reprocessing SNF could be applied for any of type of organisational model, but is currently limited by the legislation. While the regulatory framework is to be updated by the year 2027, no details on the content of the renewal concerning final disposal are yet available. This will be analysed during the last year of the SMRSiMa project.

Finally, regulatory safety oversight of organizational, management and leadership aspects in SMR lifecycles were studied. The focus of SMR discussions is primarily on technology and economic aspects, with less emphasis on human and organizational factors (HOF), management, and leadership. This lack of attention risks late or insufficient consideration of these critical aspects, potentially leading to issues in ensuring safety and effective management. The scenarios discussed highlight assumptions about future SMRs, such as harmonized regulation, inherent safety features, and operation as fleets of remotely operated units. Ensuring safety and gaining public acceptance are essential, and a clear division of roles between the license holder and main operators is necessary to avoid challenges. Engaging with nuclear experts to envision and discuss desired futures and related assumptions is one way for staying prepared and vigilant, and being mindful of unintended consequences to maintain high level of safety and safety culture during the transition. The nuclear industry must avoid oversimplifying safety interpretations, especially with increased automation and organizational complexity anticipated for SMRs.

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