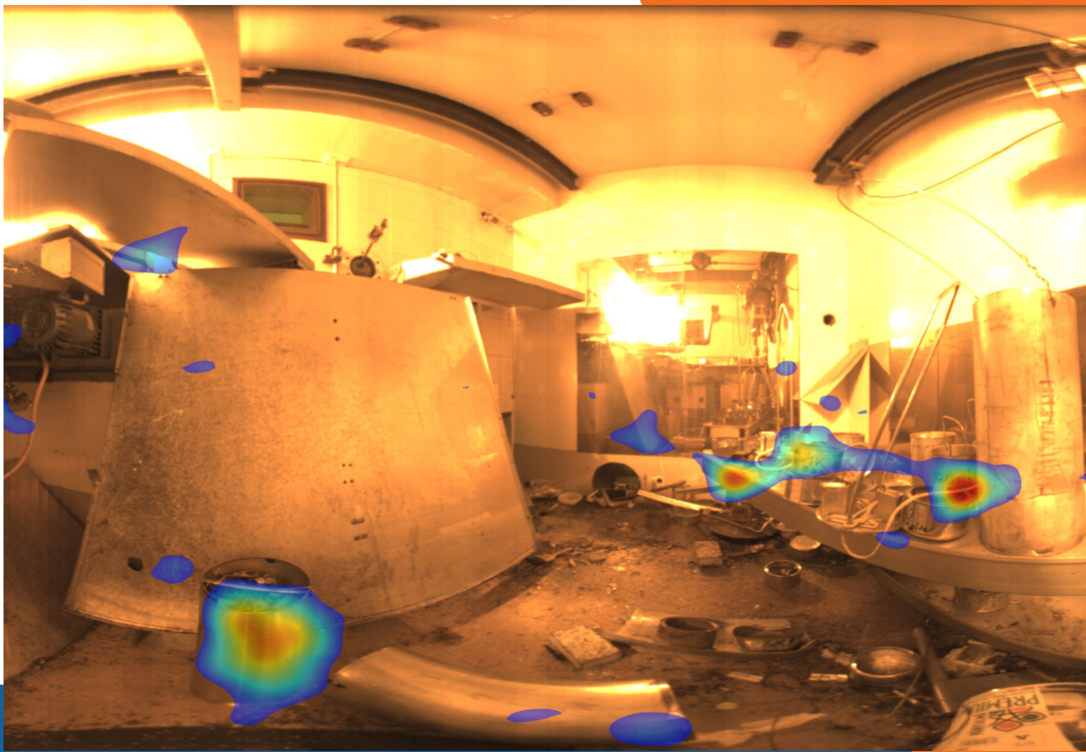

Ecosystem for New International Decommissioning Services

Final report - dECOmm project 2019-23

Olli Soppela | Markus Airila | Tatu Harviainen |
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Cover image: Gamma camera view inside a hot cell in Otakaari 3 before decommissioning. Picture by Createc and Fortum.

Preface

Decommissioning of nuclear power plants (NPP) presents a significant business opportunity with high market potential, in Europe and globally. These projects are large-scale and costly, requiring the specialized knowledge of companies in the nuclear industry as well as conventional demolition expertise. The dECOmm project has united these diverse players, fostering domestic collaboration and also engaging international partners through several EU projects.

Decommissioning decades-old nuclear power plants is not without its challenges. Reality often does not follow the documents due to undocumented decisions and poorly documented modifications. This makes it impossible to reliably plan and automate decommissioning based on existing documents. A unique aspect of the decommissioning market is that it requires years, even decades, of services for analysis, measurement, and planning before the actual demolition takes place.

Applying and developing modern approaches can move the nuclear industry forward and ease the present help long-term planning and execution processes. Safety improvements, better mutual communication between operators, contractors, regulators, and other stakeholders as well as faster implementation and reduced costs can be achieved by same smarter solutions.

Furthermore, decommissioning projects represent a form of circular economy business. As ecological issues and circular economy approaches become increasingly important, projects like dECOmm play a crucial role in promoting sustainable practices in the industry.

The dECOmm project, one of the first co-innovation projects funded by Business Finland, has proven the efficacy of an ecosystem approach in fostering innovation and societal impact. The project was based on close cooperation between seven companies and VTT, forming an effective ecosystem with research and accelerated development supporting each other. We managed to create new skills and frameworks that will enable companies and business networks to accelerate the development and launch of their products and services to meet the nuclear power plant decommissioning market needs.

Despite the challenges posed by the COVID-19 pandemic, which heavily impacted networking activities, we continued organizing the successful Open

Business Days by holding one event virtually. While it was a success, we have since learned the value of face-to-face networking. Our relationship with the DigiDECOM community, coordinated by IFE in Norway, has been particularly rewarding. The recent DigiDECOM conference in Helsinki exemplified this spirit of collaboration.

This project has been a journey of research, collaboration with participating companies, and both domestic and international networking. We are grateful to Business Finland for introducing the co-innovation funding instrument, which has also since this project been widely used at VTT to innovate efficiently with companies and bring impact to society in our core expertise areas. We look forward to continuing this journey of innovation and collaboration in the nuclear decommissioning industry. The lessons learned from this project will undoubtedly inform future endeavors and contribute to the ongoing development of safe and efficient decommissioning practices.

Espoo, Finland, 3 November 2023

In the spirit of continued collaboration

Authors

Contents

List of abbreviations

3D	Three Dimensional
ACRE	Aalto University Campus and Real Estate
AMR	Advanced Modular Reactor
AR	Augmented Reality
BF	Business Finland
BIM	Building Information Model
BNCT	Boron neutron capture therapy
BNG	Babcock Noell GmbH
BWR	Boiling Water Reactor
CNL	Canadian Nuclear Laboratories
CoDNI	Committee on Decommissioning of Nuclear Installations
Cobot	Collaborative Robot
DOE	Department of Energy
EcoSMR	Ecosystem for Small Modular Reactors
FiR1	Finland Reactor 1 (TRIGA)
HSE	Health, Safety & Environment
IAEA	International Atomic Energy Agency
IAND	Innovative and Advanced Nuclear Reactor Decommissioning
I&K	Information and Knowledge
LiDAR	Light Detection and Ranging
MEAE	Ministry of Economy and Employment in Finland
MW	Megawatt

MWh	Megawatt hour
NEA	Nuclear Energy Agency
NDA	Non-Disclosure Agreement
NPP	Nuclear Power Plant
NuDRisk	Nuclear Decommissioning Risk Ontology
O&M	Operations and Management
PMO	Project Management Office
PRIS	Power Reactor Information System
PWR	Pressurized Water Reactor
R&D	Research and Development
SMR	Small Modular Reactor
STUK	Radiation and Nuclear Safety Authority in Finland
TRIGA	Training, Research, Isotopes, General Atomics reactor
VR	Virtual Reality
VTT	VTT technical Research Centre of Finland Ltd
XR	Extended Reality
YVL	STUK Regulatory Guides on nuclear safety and security

1 Introduction

Nuclear energy has been elevated in discussion as an important component in the energy and environmental solutions of the 21st century. Especially, the next generation reactor types with passive safety features have potential also outside the traditional nuclear applications. However, when innovating new nuclear we need to keep in mind the total life cycle of a Nuclear Power Plant (NPP); how to dismantle, recycle or reuse the plant and site economically and socially at its best.

In 2020, there were 442 nuclear power reactors in operation, 53 under construction and 187 in permanent shutdown; however, only 17 nuclear reactors have been fully decommissioned (Invernizzi et al., 2020). As shown in Figure 1, most of the reactors in the current fleet have been in operation for around 40 years (IAEA PRIS). This will put a strain on the decommissioning resources in the future as many of the reactors require dismantling simultaneously. However, due to ongoing lifetime extensions initiated by the global energy crisis, the peak for decommissioning will be postponed.

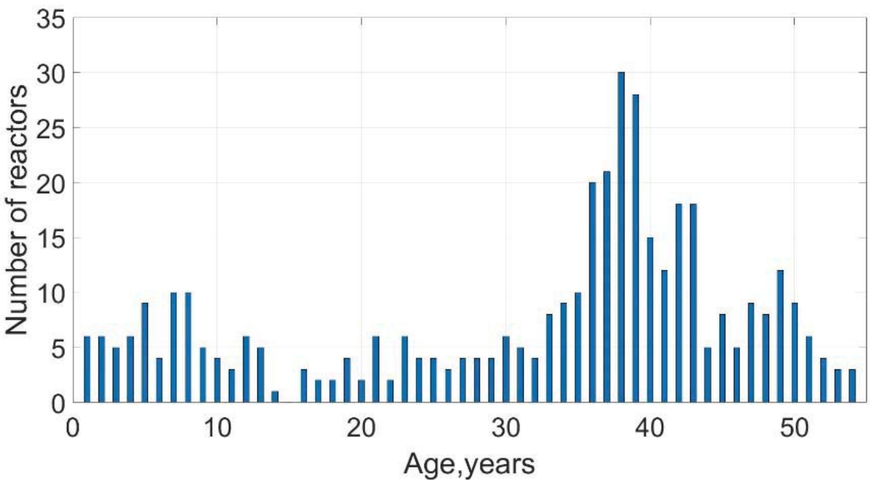

Figure 1. Global age distribution of nuclear power plants in 06/23.

Decommissioning represents the last phase of the life cycle of a nuclear power plant. It has been included in IAEA's regular programmes since 1985 (Laraia, 2003). The focus was first on nuclear power plants and to a lesser extent, research reactors but already in the beginning of 2000's, programmes expanded to small medical, industrial and research facilities (Laraia, 2003).

In practice, decommissioning project is never the same in any NPP. When the first wave of NPPs was built, planning the decommissioning was not as important part of the planning phase as it is nowadays. In addition, the documentation of the changes during use, a phase that normally lasts for decades, has been incomplete in many cases. This makes it challenging for present-day operators and contractors to execute fast and cost-efficient decommissioning.

On the other hand, decommissioning is not a profitable part of the business for the operators. Decommissioning of many old NPPs is now the responsibility of the state, thus making the cost a public interest. It is not surprising that safe but cost-efficient decommissioning is an important topic in the industry.

The dECOmm project activities have been aligned with other Finnish Nuclear Ecosystem activities; EcoSMR that focused on small modular reactor (SMR) research and EcoFusion which is actively researching business opportunities for Finnish organizations in the Fusion Energy sector. Sharing knowledge and research results, facilitating stakeholder dialogue for increased collaboration and organization of joint-seminars and –publications in international conferences have been the main methods of cross-pollination activities between the Finnish Nuclear Ecosystems. One of the successful events was the Open Business Day.

Figure 2. Open Business Days brought Finnish Nuclear Ecosystems together.

The dECOmm project has identified decommissioning business opportunities for new SMR projects, collected forecast information about the size of European nuclear energy portfolio and gathered information about the waste streams and volumes of SMR and Fusion Energy projects. The joint seminars and publications have enhanced the research and industrial collaboration and forecast capacity of participating organizations and individuals.

The project also introduced the ecosystem's commercial delivery capabilities in a Decommissioning White Book, where each member organization had the opportunity to present their offerings for the large European decommissioning projects. The company projects conducted in conjunction with the dECOmm project are also more broadly described in the Decommissioning White Book.

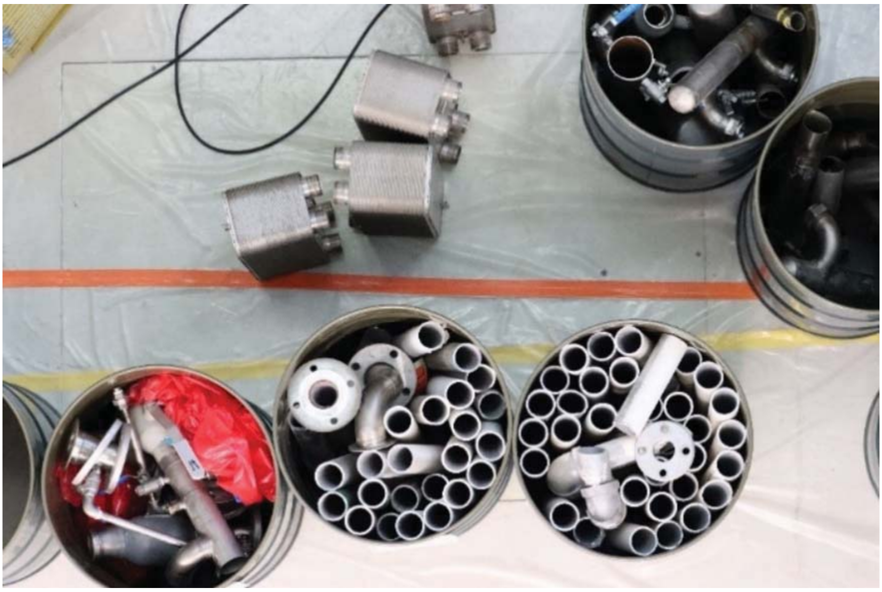

Figure 3. Decommissioned primary circuit tubes for free release from the FiR 1 reactor.

1.1 What is decommissioning / dismantling?

Nuclear decommissioning is the final stage in a nuclear facility's lifecycle, where it is taken out of use and its site is prepared for other purposes. Various definitions have been provided, from different viewpoints. A nuclear regulatory viewpoint is reflected in the following definition (IAEA 2014): "the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility". An influential reference book (Bayliss and Langley, 2003) defines nuclear decommissioning from a process viewpoint as follows: "The process whereby a nuclear facility, at the end of its economic life, is permanently taken out of service and its site made suitable for other purposes". Regardless of the definition, the decommissioning follows the main phases presented in Figure 3. The main stages include activities such as planning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.

1.2 Decommissioning process and roles

The decommissioning process starts at the final shutdown of the plant. It can generally be divided into the following main phases (Bayliss and Langley 2003):

The phases are as follows (figure 5):

- planning
- defueling
- dismantling
- nuclear waste handling
- decontamination clearance
- site release

The phases follow roughly each other. In practice, some phases may proceed partly simultaneously; for instance, even if demolition preparation follows the principles and processes defined in planning, part of the demolition preparation can be performed when general-level planning is still going on. An example of this is the planning of the demolition of such parts that can be removed already before the permission for decommissioning – parts that block the way to the reactor.

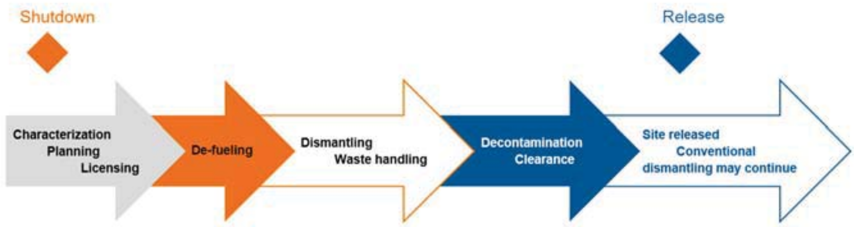

Figure 4. Simplified phases of decommissioning.

Strictly taken, a nuclear power plant cannot start decommissioning directly from the operational phase. In between, a **transitional phase** is needed, at least in the form of gradually diminishing the nuclear reaction so that there is no process going on when demolition starts. Also, key personnel to perform at least planning must be chosen before entering to the decommissioning phase. In the following, each phase is presented mostly in a general level.

The **planning** process is important to perform in an appropriate way and extensively about the relevant matters. In the planning stage, it is essential to well define what the result of planning shall be. The better it is defined, the easier it is to identify correct people to the responsibilities in question. One goal of planning is

Figure 5. Decommissioning process phases have strict boundaries in the physical working spaces.

risk avoidance – it is something that is to be considered. Fluent teamwork is vital as only a few tasks can be planned by a single person.
Planning results in accumulating documents and part of the plans are also completed by time. This process, along with document version management, must be also defined and thereafter implemented carefully.

In all big projects, decommissioning projects included, efficient communication is vital. It includes both communication between stakeholders and the documentation of information so that it is available for future needs. Timetable is important to define, too, so that there is enough time to perform well.

As decommissioning is work based on collaboration and cooperation between owner and other stakeholders, interaction needs to be flexible and intensive; frequent contact is one prerequisite for this. During corona pandemic, planning was mainly performed independently at home, so this work had to be supported, including motivation.

Defueling in nuclear decommissioning refers to the process of removing and safely extracting the fuel assemblies or fuel rods from a nuclear reactor that has reached the end of its operational life or needs to be shut down permanently. This step is a crucial part of the decommissioning process, as it aims to minimize the potential risks associated with the radioactive materials within the reactor. Defueling typically involves carefully transferring the radioactive fuel to secure storage or disposal facilities, ensuring it is no longer a hazard to the environment or public safety.

After the defueling, the **dismantling** of the reactor can be started. Dismantling (breaking down and transferring away of equipment and systems) and demolition (knocking down and transferring away of building structures) preparation include preparatory measures at the site and detailed planning. During this phase, also the permission to start dismantling and demolition is obtained. Again, competent personnel to perform preparations is vital. Now collaboration becomes more concrete because owner and subcontractor(s) start both to work at the site. Rules and responsibilities must be shared, and the social aspect must be considered as well.

The reactor is removed in the dismantling phase and the structures around it are demolished as well. All ways to perform are agreed on beforehand; something can be rehearsed at the site as well but in principle, there should be nothing to learn at this phase. Instead, procedures must be followed, and good work practices applied.

Nuclear waste management includes preparatory measures for accepting waste, waste transportation and acceptance, and the transition of responsibility over the waste from owner to the party receiving and taking over the waste. Competent personnel, trained to perform according to specific procedures, is needed to do all this.

Figure 6. Operator at work during the dismantling of reactor core internals of the FiR 1 research reactor.

In the case of nuclear facility decommissioning, waste management is performed in the vicinity of the reactor. Still, it is done in such a way that the final positioning of the waste is considered. Packing needs to be performed so that the package is transported without opening it in any phase of the process to the final disposal site. Waste management process is defined in such a way that the possibility of human error is minimized. Much of it is automated but of course, there is also human share of the work. Especially documentation requires care as there an error may easily occur. The measurement of radioactivity and the packing is done so that there will be no need to do it again. Here, competent experts are the key for ensuring this goal is reached. Waste transportation is also human dependent, providing a possibility to human error.

The lifting of used fuel from the reactor is manual work, aided with a crane. The safety of this work is mechanically ensured; the reactor building is covered with layers preventing leakage to the outside world. Finnish regulator, and IAEA, have defined the safety level, which must be obtained during the procedure and usually the requirement level is exceeded. The risks related to spent fuel handling and transportation are well known, and the probability for these types of accidents occurring is small. However, the transportation of the used nuclear fuel from the site is the most critical phase in the decommissioning process, as nuclear fuel is the most radioactive part in the reactor.

Decontamination clearance is the last phase in nuclear decommissioning where the verification that a facility or area previously involved in nuclear activities has been effectively decontaminated to a level that is safe for unrestricted use and that the generated waste is responsibly managed. This crucial step ensures that residual radioactive contamination has been reduced to acceptable levels, meeting regulatory standards, and minimizing potential health and environmental risks. Various techniques up to measurements and monitoring are employed to achieve decontamination clearance, allowing the site to be repurposed or returned to its natural state without posing radioactive hazards.

At the end of the decommissioning process, the site is optionally landscaped, and **released** to any other, further use. Decommissioning license is terminated.

Figure 7. Waiting for permission to transport a radioactive material sample from FiR 1 structures for analysis.

2 Information and Knowledge

Various sorts of information and knowledge (I&K)– pre-existing or generated and collected during decommissioning of the facility – are necessary or useful for decommissioning itself or for broader purposes. In this section, we go through some central I&K kinds and possible sources.

2.1 Data and knowledge needs

2.1.1 Needs of the decommissioning project

The final shutdown of a nuclear facility represents a turning point in I&K needs and availability. Activities at the facility are subject to a complete makeover, as production (consisting of nuclear, mechanical, and electrical engineering activities) gives way to demolition, waste management and disposal, and recycling (mostly civil engineering activities). Much of the I&K that has been needed to operate the plant becomes obsolete. Instead, I&K is needed about systems and structures that were paid scant attention to when the plant was operating. Cases in point are for example underwork and non-safety-critical piping.

Need for information about radiation levels, characteristics, and radionuclide contamination is an I&K need that is specific to the nuclear sector. This information is needed for work arrangements, waste handling (e.g., decontamination) and other waste management purposes. Radiation measurements and material sampling are parts of the decommissioning process.

Also, other information is needed about the systems and structures of the facility. This information concerns their location, position, size, weight, geometry, and materials. It is needed for decisions concerning handling (manipulation, processing, moving, storing, packing and transport), recycling and final disposal.

2.1.2 Needs of nuclear and radiation safety regulators

A nuclear and radiation safety authority's role is to supervise the facility and the decommissioning work to ascertain that the process and its products – the site after decommissioning, and the stored radioactive waste – do not cause significant risks related to ionizing radiation to workers, the public, and the environment, and fill the requirements set by regulation.

In Finland, the regulation consists of nuclear energy law, nuclear energy statute, and various regulatory documents produced by STUK. Concerning decommissioning, the most relevant of these documents is YVL D.4 (STUK, 2019). It has several requirements to the license holder concerning information that must be acquired, stored, and reported; for example, paragraphs 419-421

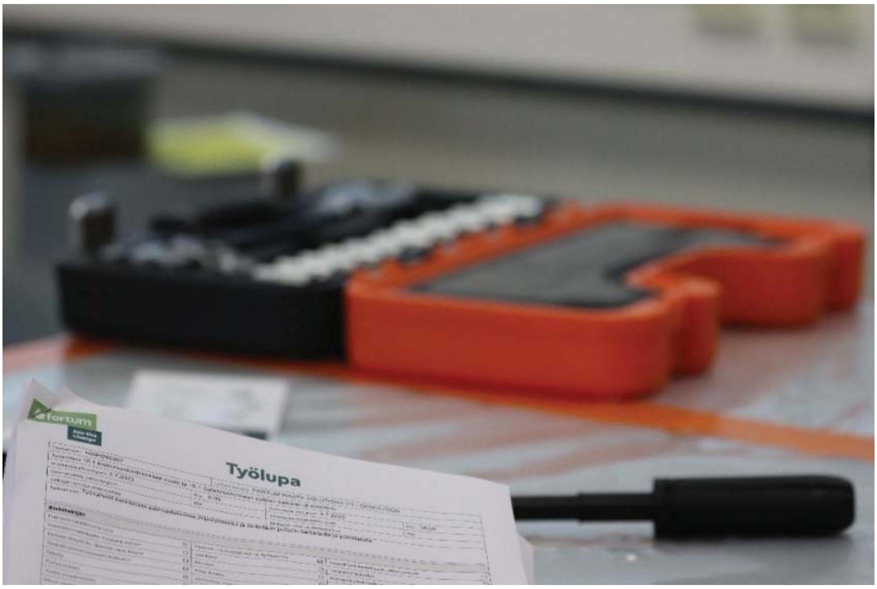

Figure 8. Each worker and work phase requires work permits to ensure safe procedures.

dictate what information must be acquired and recorded about nuclear waste, and paragraph 421 mandates that this information must be reported to STUK. Paragraph 425 tells that “At a permanently closed nuclear facility, a comprehensive activity and contamination level survey and recording programme shall be implemented [..] The activity and contamination level data shall be updated as the decommissioning proceeds whenever significant changes to them can be assumed to have occurred”.

2.1.3 Needs of environmental authorities

An environmental impact assessment for nuclear facilities is mandatory in Finland (STUK 2019, paragraph 108), as well as for example in the USA (Jain ea. 2012, p. 649). information is needed on issues that may cause burden or risk to the environment: hazardous materials either existing on the site or to be used in decommissioning, possibility of contamination of land masses, and so on. In addition, the information about the site and its surroundings, work processes etc. is needed to the extent that they are relevant: geology, water systems and so on.

2.2 Data and knowledge sources

Various kinds of design documents – floorplans, system drawings, piping plans etc. – are a central source of information for decommissioning. In Finland, the license holder must submit comprehensive documentation of a nuclear facility to the nuclear regulator when applying for construction license, and the license holder must store and maintain them. However, it cannot be taken for granted that comprehensive documentation would be available in all countries that have nuclear power.

Nuclear facilities also generate a sizeable number of reports on their operation. However, this information is likely to be of limited value in decommissioning. Incident reports may be useful in specifying where to conduct radiation measurements in preparation for decommissioning.

Building Information Models (BIM) are digital representations of a facility or structure that integrate 3D geometry, spatial relationships, data, and information about the various components and systems within the building. BIM is primarily associated with the construction and operation phases of a facility's lifecycle, but it can also be valuable in the context of nuclear decommissioning. In nuclear decommissioning, BIM can be applied in the following ways: Visualization and Planning; Data Management; Safety Assessment; Collaboration and Communication; Asset Recovery & Documentation and Compliance.

BIM models provide a comprehensive visual representation of the nuclear facility, including its structural, mechanical, and electrical systems. This visualization aids in planning the decommissioning process by offering a clear overview of the facility's layout and infrastructure. BIM can incorporate detailed data about the building's components, materials, and systems. This information can be crucial in the decommissioning process for tracking and managing the removal of radioactive materials, waste, and equipment, as well as ensuring regulatory compliance. BIM can be used to simulate and assess the safety of decommissioning procedures. It helps identify potential hazards, evaluate risks, and plan for the safe dismantling of nuclear facilities. BIM can facilitate collaboration among various stakeholders involved in the decommissioning project, such as engineers, regulators, and project managers. It ensures that everyone is working with the same updated information, reducing errors and miscommunication. Built models can aid in identifying and assessing the potential value of salvageable equipment and materials within the facility, optimizing asset recovery and reuse opportunities. Modelling also supports the creation of detailed

Figure 9. Various measurements are required for safe working and its documentation.

documentation required for regulatory compliance and reporting during the decommissioning process. By utilizing BIM in nuclear decommissioning, project teams can improve efficiency, reduce costs, enhance safety, and ensure that the decommissioning process is carried out effectively and in compliance with stringent regulations.

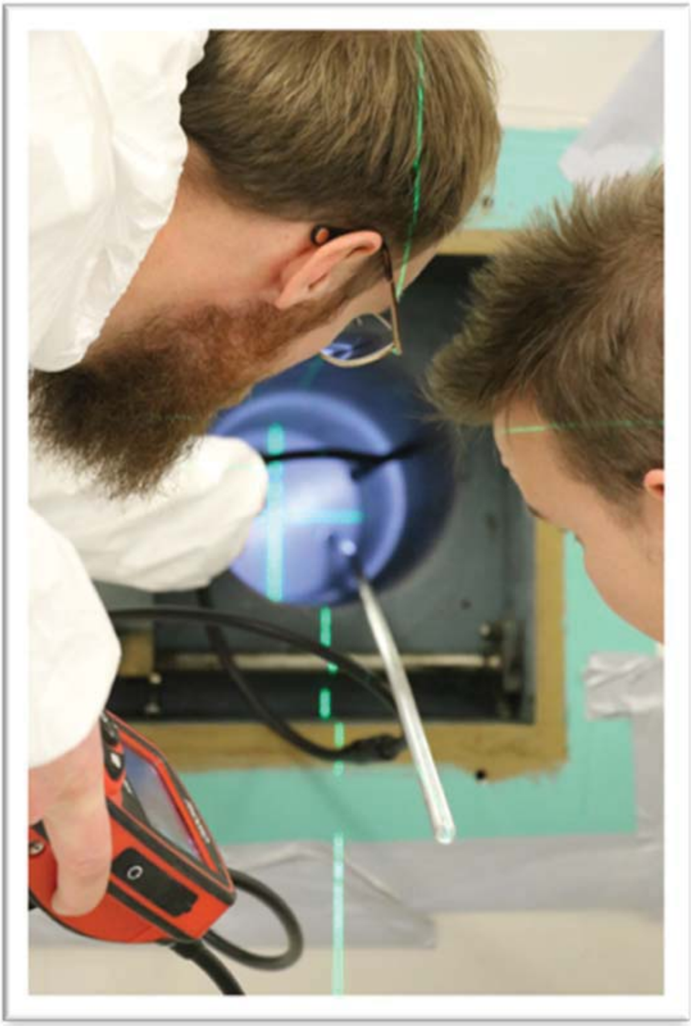

Figure 10. Laser measurements are conducted to have a precise picture of the structure and work conducted.

2.2.1 Measurements

Various kinds of measurements are usually the most accurate and sometimes the only possible means of getting information needed in decommissioning. Exact dimensions and locations of various structures and systems may be found out by measuring, although it may be simpler to look them up from plant documentation. On the other hand, radioactivity levels at different points must be measured to obtain accurate figures.

3 Robotics and data

Developments in sensor technology, robotics and digital tools for spatial data processing have opened doors for digital transformation, where the operational environment can have a digital representation that enables more efficient information sharing and better situational awareness. Especially for environments with unknown, possible hazardous conditions, autonomous platforms carrying sensing technologies enabling characterization of those conditions can significantly enhance the planning and operations. Novel solutions based on combination of robotics, sensing technologies and digital twins can support and replace information resources previously inspected and archived as individual documents. In this chapter, building blocks of such solutions are described deriving results from practical hands-on pilot testing carried out in the dECOmm -project.

3.1 Robotics

Robotics have potential to free humans from most dangerous, dull, and dirty tasks. This will improve the working conditions and well-being of workers. Especially in hazardous conditions, such as nuclear decommissioning, robotics can increase the safety and allow operations in areas restricted from human operators. Today, clearly largest area applying robotics is manufacturing. In manufacturing, stationary robots have been successfully used and proven added value thanks to the relatively easy deployment conditions, namely non-changing operation environment and relatively simple tasks that can be solved with pre-trained motion sequences.

Development of mobile robots is now opening possibilities to expand the usage of robotic solutions in new environments and new use cases. Autonomous outdoor robots are being deployed commercially in outdoor environments, e.g., wheeled robots as last-mile delivery robots in cities, legged robots for search and rescue after earthquakes, and drones for forest fire management. However, mobile robots are not yet widely used in areas characterized by continuously changing environment requiring deeper level of environment contextual understanding and complex operations.

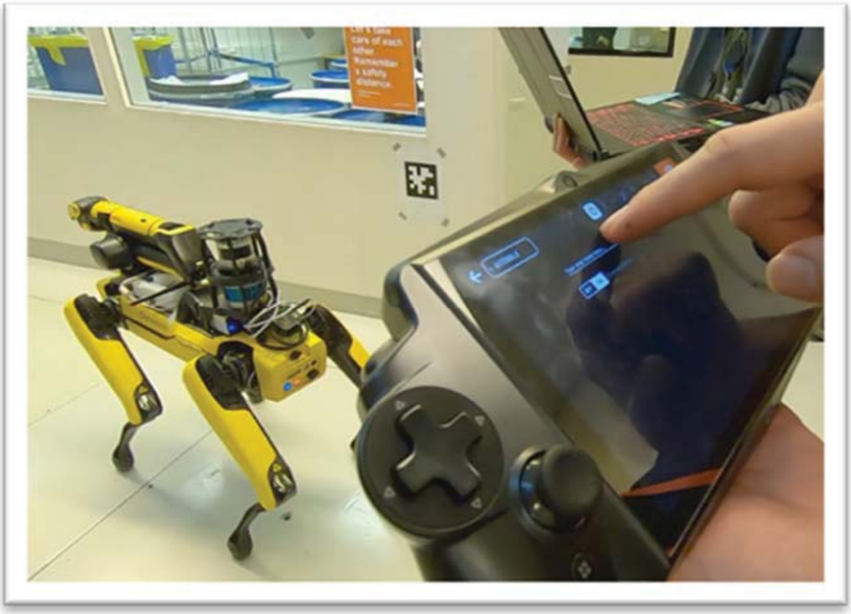

Figure 11. Boston Dynamics’ Spot robot measuring FiR1 radiation levels with dosimeter and Lidar.

3.1.1 Components for robotic solutions

Meaningful solutions for robotic operations are built with various components dependent on the required performance of the system. Platform provides the mobility of the system. Depending on the desired task the mobility function can be anything from stationary to flight capacities. Next layer of required components are the sensors, which provide the environmental awareness for the system. Again, depending on the given tasks, the range of sensors is selected based on the required performance. Third layer of components are tools or actuators that enable the system to manipulate its physical environment. Tooling functions are not necessarily required if monitoring and analysis are the only tasks of the system.

Today, most of the mobile robots offered as a turnkey solution rely on well tried and tested sensor modalities, namely cameras for vision, LiDARs and simple acoustic or radar proximity sensors for collision avoidance and mapping of the environment. Many other sensing modalities are becoming viable alternatives as sensor hardware is developing further. For example, imaging radars, thermal cameras and hyperspectral sensing can be of high value as an additional sensing modality depending on the use case. At the moment, integration of the additional sensing modalities requires tailored modification to the robot platforms.

3.2 Data Collection

In case of NPP decommissioning, original plans and documents may still be in paper format and many of the changes done over the years of operation may be difficult to track. For efficient planning of the decommissioning, up-to-date data of the environment and environment conditions are needed. Capturing and refining data from the real environment can be more efficient than converting old paper format documents manually to a digital format.

In dECOmm project, building of digital representation of the operational environment manually from stationary LiDAR scans was performed as well as scanning with mobile LiDAR embedded with a robot platform was tested. Scanning with stationary scanner is much more labour intensive compared to the use of robot platform for the task but can provide higher quality data. However, in both cases, extensive manual work is still required in order to transform raw point cloud data produced by the LiDAR captures into a structured information model representing the environment as 3D surfaces and hierarchical object structures. Solutions for more automatically bridging the gap from scanned data into a building information model are still much lacking and in dECOmm project, the model used as a digital twin of the NPP under decommissioning was manually modelled based on the stationary LiDAR scan, a task which required substantial effort.

Benefit of the digital twin approach in addition to easier spatial visualization and management of the data is the ability to combine many different types of data associated with the environment geometry.

Figure 12. Special Personal Protective Equipment (PPE) is required in many of the decommissioning working phases. Additional shoe boundaries are used to eliminate spreading of contamination outside higher-risk work locations.

Novel sensing solutions utilizing various sensors could be used to create and maintain the digital twin with better scalability. Regularly performed measurements of the environment can increase situational awareness by detecting changes in the environment. The sensors can be either fixed in position or attached to mobile robots, thus being able to cover larger areas. Fusing the obtained sensor data with the underlying digital models needs research attention, regardless of the creation method of the model.

Being able to bind data from various sensors to the environment in real-time opens the door for spatial visualizations of the data. The visualization can be realized with various devices depending on the need, from computer screens to VR and AR glasses. Especially with AR, the real-world location of the user can be used as an additional input modality for increased interaction potential with the IM.

3.2.1 Spatial data

In case of multimodal spatial data collection, data fusion is an active area of research. In terms of digital modelling, combination of real-world geometry captured with the LiDAR, multispectral imaging data from the hyperspectral sensor and other novel sensor-based environment data with the BIM model is a challenge currently lacking well-known solutions. In this project, novel sensing solution derived data fusion and association with the BIM model to create a digital model of the real operational environment will be developed beyond current state-of-the-art.

3.3 Data analysis and visualization

Efficient means for visualizing the data collected by the novel sensing solutions and situational awareness derived from the collected data enables optimized operations in the environment and improved communication between stakeholders. Display devices and associated visualization solutions for Augmented Reality (AR), Virtual reality (VR), or Extended reality (XR) have reached technology readiness level enabling common consumer use. Immersive data visualization with extended reality technology heavily relies on the real-time 3D rendering hardware and software.

Much of the current state-of-the-art solutions for the real-time 3D rendering have originally been developed for the computer game development purposes. Real-time 3D platforms, such as Unity and Unreal Engine, are today used widely in many industry sectors beyond gaming for data visualization purposes and are de facto platforms for XR applications. However, they still rely on content formats specifically tailored for the real-time visualization rather than being able to visualize design data coming from the BIM models or sensor data coming from the novel sensing solutions. Translation of sensor and design data into formats that enable efficient immersive real-time data visualization, as well as real-time visualization methods enabling efficient sensor data visualization are at the moment topics requiring further research.

Data analysis is needed to be able to collect and cumulate multisensory data from the operational environment into a continuously updating digital representation. First step in the data processing required for building a digital model of the operational environment is the sensor fusion, where data from various sensors is assembled into a one cohesive coordinate space. Also design data, when available for the operational environment, is desirable to be included in the data fusion and assembly of the digital model.

Data produced by the different sensing technologies do not typically provide the information needed to accurately align the data accumulated from the sensors spatially with data from other sensor modalities or the design data. Dedicated methods are needed for multisensory data accumulation and fusion for, for example, aligning a 3D reconstruction of the environment geometry assembled from mobile LiDAR with the radiological characterization data collected with a radiation dose meter and design data in the form of a building information model. In dECOmm project one approach for such data fusion was developed.

Figure 13. Measurements data can be fed into data layers in the Building Information Models (BIM).

3.3.1 Digital twin

Building and information modelling (BIM) has been increasingly adopted in various industry sectors. BIM has capability in composing information concerning hierarchical model beyond strictly structural parameters or visualization, to include information concerning scheduling, material parameters and generic data that can be used in the use phase for facility or asset management. Development of BIM methodology towards creation of dynamically updating replica of the operational environment, concept often referred as a digital twin, has focused on interconnecting sensors in physical assets with the information model.

With further data analysis, based on the collected and fused data, environmental changes, actual locations and poses of dynamic elements and critical conditions in the environment can be automatically detected. In dECOmm project, methods for detecting differences between scanned environment geometry and the design model of the environment were developed. Also, there are methods available for object recognition and model-based tracking of the objects detected from the sensor data. Further development and integration of these methods would enable synchronization of the design data with the actual environment conditions as observed by the sensors, thus enabling a creation of a real-time updated digital model.

4 Decommissioning market and business

Decommissioning business has very original characteristics. No case nor market environment is the same. This is one of the reasons why decommissioning projects take years, sometimes decades. Repeatability and predictability are the more challenging the older and larger the NPP is.

Decommissioning is a cost that currently must be included already in the early design phase and when building the business case. When the NPPs were built in 50s and 60s this was not always the case. Now these liabilities are carried by the plant owners, often states, and for example in the case of old east European countries shared, also by EU.

4.1 Decommissioning Markets

Estimations of the global nuclear decommissioning total market size for 2035 is estimated to be $111B. Currently there is in total 182 civil nuclear reactors shutdown and it is estimated that around 200 commercial nuclear reactors are to be shut down between 2020 and 2040 *(WNN 2020).* Of these shutdown reactors 61% are in Europe *(IAEA PRIS 2023).*

The forecasts for the European decommissioning markets have been through an unexceptional turbulence during the past decade. The future role and classification of nuclear energy in the European energy system has been under active debate which has led countries to change their positions considering

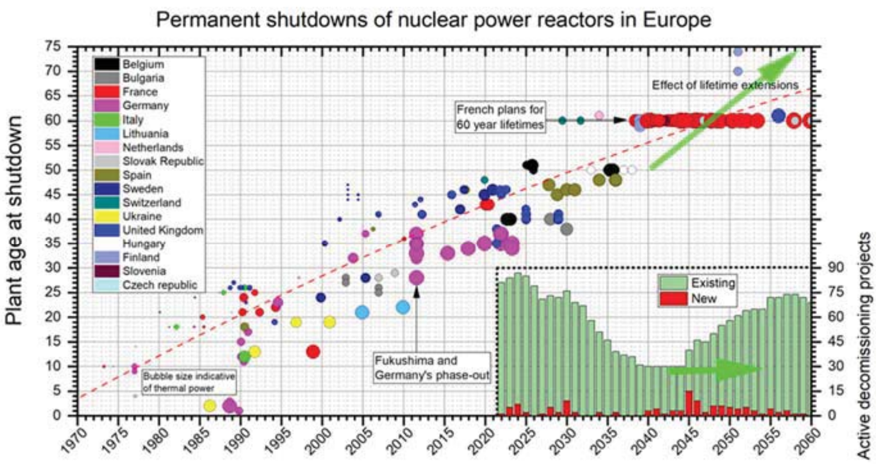

Figure 14. Shutdown schedule of European nuclear reactors (Kaartinen 2023).

national energy strategies. Multiple simultaneous decisions on early shutdowns of nuclear fleets in the aftermath of the Fukushima Daichi nuclear accident in 2011 caught the nuclear licensees by surprise. The decision for early shutdowns was later questioned in most of EU countries during the gas crisis beginning in 2020 due to the Russian invasion of Ukraine and the following gas delivery contract challenges. Uncertainty about the future of European energy markets put many nuclear shutdown projects on hold while extension applications are considered.

Error! Reference source not found. illustrates the most recent permanent shutdown schedule for European nuclear power plants. The colour marks the reactor's location, size of the bubble indicates the thermal power of the reactor and the red dotted line the average usage time of the plant.

Developing the necessary scalable decommissioning capacity for simultaneous decommissioning projects remains a topical challenge, since much of the European fleet has been built simultaneously. Also, the lifetime extension application schedules are aligned, and it is expected that even if the decommissioning schedules are postponed, they are to be proceeding simultaneously. The main bottlenecks in decommissioning projects are going to remain being the lack of skilled workers, complex license-dependent management systems, and large amounts of documentation and plan iteration.

4.2 Decommissioning as Business

The license holder of the nuclear installation is responsible for funding and securing the decommissioning activities of the licensed installation. Easy way to secure the funding is to deposit a fixed fee from each sold MWh to the decommissioning and waste management fund, which will ultimately finance the decommissioning and spent nuclear fuel management processes. The financing of a research reactor decommissioning requires the waste management fee to be included in the research and commercial activities involved.

The license holder rarely themselves do the practical decommissioning work. Typically, a large contractor with sufficient experience, resources and most cost-efficient offer wins a decommissioning tendering process and takes over the management of the decommissioning activities. The main contractor usually hires subcontractors to take care of certain phases or limited smaller projects within the main contract. These 1st tier subcontractors are usually still very large companies able to manage and finance operations of tens of millions of euros. The 1st tier subcontractor hires 2nd tier subcontractors to provide practical tools, methods, processes, equipment and

4.2.1 Typical business case

It's a good start to say that there is no typical business case. Therefor this description is an approximation and real-life cases can and do vary significantly due to the factors like national regulatory requirements, individual NPP, access to resources, and the selected decommissioning strategy: immediate dismantling, deferred dismantling.

During these steps it is important to communicate actively not only with the authorities but also with the local community and other stakeholders. Actions like environmental assessment are important tools to support this.

In many cases, financing is a significant concern already before the Stage 1 (Table 1 below). If funding for decommissioning has not been ensured during the plant's lifecycle, as has been done in Finland by depositing enough funds into the Nuclear Waste Management Fund, financing must be arranged through other means, often with public funding. However, this is not the focus of this examination, so we will not delve further into this topic. In decommissioning business issues like national legislation, regulatory requirements, type of NPP and ownership structures have a big impact on how to proceed with the decommissioning. This has the biggest impact on the top level of the decommissioning organization, strategies that are possible in a specific case, and main contractors and their responsibilities and roles.

From the 2nd and 3rd tier subcontractor point of view, all projects need special skills, services, and equipment. Politics, procurement policies, and geographical location have a greater impact on business opportunities, together with previous business relationships and reputation in the business.

Figure 15. Skilled labour is required in all work phases in nuclear decommissioning.

Table 1 - Main stages of the decommissioning process in most cases

Project Stage	**Schedule** (prior/post shutdown)	**Subcontracting needs**
Stage 1: Preparatory Phase (prior to shutdown)	1-5 years prior	consultancy, advisory, prelim. decommissioning plan
Regulatory Approval	1-2 years prior	environmental assessment, document management
- regulatory approval for plans and funding		
Pre-Decommissioning Activities (prior to shutdown):	1-2 years prior	consultancy, advisory
- detailed decommissioning plan		3D/4D models, digital twin
- establishing organization and oversight		needs for subcontracting
Stage 2: Shutdown and Post-Operation		
Immediate Shutdown (reactor shutdown):		monitoring and evaluation
- safely shut down the reactor		
- remove fuel from the reactor and move to the spent fuel pool		
Cooling-off	1-5 years post	monitoring, measurement
- reactor cool down and reduction in radioactivity		–
Stage 3: Deferred Dismantling (varies based on strategy)	1-50 years post	
Defueling	1-5 years post	
- removal of the remaining fuel and placement in dry cask storage **or**		
- transfer to a centralized facility		–
Decontamination	5-15 years post	
- remove loose or removable contamination from equipment and structures		efficient methods, equipment, machinery, verification, labor
Maintenance and Surveillance	over the project	monitoring and evaluation
- monitoring for any changes in radiological conditions		–
- maintaining systems and structures		–
Stage 4: Decontamination and Dismantling	10-40 years post	keeping data and digital models up to date
Decontamination and Dismantling	1-30 years post	efficient methods, equipment, machinery, verification, labor
- dismantle and remove contaminated components and structures		–
- decontaminate surfaces and materials		–
Waste Management		
- package and manage radioactive waste		–
Stage 5: Site Release	30-60 years post	
Cleanup and Verification	30-50 years post	
- final radiological surveys and assessments		monitoring, measurement
- remediation of any remaining contamination		efficient methods, equipment, machinery, verification, labor
Regulatory Approval for Site Release for unrestricted use	50-60 years post	consultancy

4.2.2 Business models

It's important to note that the choice of business model should align with regulatory requirements, financial capabilities, and the specific characteristics of the NPP and its surrounding environment. Additionally, engaging with stakeholders and obtaining regulatory approval are crucial steps in implementing any business model for NPP decommissioning.

Owner-Operator Model
The owner assumes full responsibility for the decommissioning process, including planning, funding, and execution. This offers direct control and decision-making flexibility, but demands substantial financial resources and expertise, along with bearing all associated costs and liabilities.

Third-Party Contracting Model
Owners enlist an external company or consortium to manage the decommissioning process. This shifts technical and financial risks to the contractor, enabling the owner to focus on other operations or projects. However, it necessitates careful contractor selection and may involve complex contractual arrangements.

Decommissioning Trust Fund Model
Owners establish a trust fund during the operational phase to accumulate decommissioning funds. After plant shutdown, these funds are allocated for decommissioning activities. This provides a dedicated funding source and helps mitigate financial risks but requires meticulous financial planning as investment returns may impact fund availability.

Multi-Unit Model
In cases with multiple units on the same site, decommissioning activities can be coordinated to achieve economies of scale. This allows for resource and expertise sharing, reducing overall costs, and making efficient use of infrastructure. However, coordination among units may be complex and regulatory approval for multi-unit decommissioning may be necessary.

Phased Decommissioning Model
Decommissioning activities occur in stages, offering flexibility in resource allocation and project scheduling. This spreads costs over an extended period and allows adjustments based on evolving regulatory requirements or technologies. However, it demands careful planning and coordination to ensure safety and regulatory compliance during each phase.

4.2.3 Organization

The business when selected is but the first step in the decommissioning project. An organization that executes the project is required to bring the model into reality. As the business model, also the organization, can and will take shape according to the requirements of each project. However, the following functions need to be handled:

1. Executive Management
2. Project Management Office (PMO)
3. Engineering and Technical Services
4. Health, Safety, and Environmental (HSE) Department
5. Licensing and Regulatory Affairs
6. Waste Management and Disposal
7. Operations and Maintenance (O&M)
8. Procurement and Supply Chain
9. Stakeholder Engagement and Public Relations
10. Legal and Financial Department
11. Training and Human Resources
12. Security and Site Protection
13. Quality Assurance and Control
14. Emergency Response and Contingency Planning

4.2.4 Innovation activities

Although the decommissioning of nuclear power plants is inherently straightforward, streamlining the process has become crucial, especially with the increasing number of facilities entering the decommissioning phase. The rapid advancement of technology across various domains has been notable. Particularly, solutions based on information technology can be extensively utilized in the decommissioning of nuclear power plants.

Some most active innovation areas are (See 7. for future development foresight):

1. Remote Robotics and Automation
2. Augmented Reality (AR) and Virtual Reality (VR)
3. Advanced Cutting and Dismantling Techniques
4. Radiation Detection and Imaging
5. Waste Characterization and Minimization
6. In Situ Treatment and Decontamination
7. Digital Twin Technology
8. Materials Recycling and Repurposing
9. Advanced Shielding and Containment
10. Predictive Analytics and Machine Learning
11. Smart Sensors and IoT Integration
12. Drones and Aerial Imaging
13. Environmental Remediation Technologies
14. Decommissioning Simulation and Training
15. Regulatory Compliance Tools

The advancement of technology and innovations doesn’t materialize without activation measures. Many national and international organizations have directed and partially funded the development of solutions.

Business Finland (BF)
In Finland BF is the most important national financing body for Finnish companies and research organizations. Since 2020, BF has been funding decommissioning, fusion energy and SMR related co-innovation projects aimed at innovation ecosystem building and international export.

International Atomic Energy Agency (IAEA) Decommissioning Program
The IAEA provides guidance, technical assistance, and knowledge sharing on decommissioning best practices globally.

European Commission's Horizon 2020 Program - Decommissioning Fund
This EU-funded program supports research and innovation in nuclear decommissioning technologies, with a focus on safety and cost-effectiveness.

United States Department of Energy (DOE) Office of Environmental Management (EM) - Technology Development Program
The EM invests in research and development of innovative technologies for the clean-up and closure of former nuclear production and research sites.

Japan's Decommissioning Technology Development Project
In response to the Fukushima disaster, Japan launched various initiatives to develop advanced technologies for the decommissioning of damaged reactors.

UK Nuclear Decommissioning Authority (NDA) Innovation Program
The NDA promotes innovation in the decommissioning of the UK's nuclear sites, including funding research projects and technology development.

Canadian Nuclear Laboratories (CNL) - Decommissioning Innovation Program
CNL supports research and development projects focused on innovative technologies and approaches for decommissioning nuclear facilities.

South Korea's Decommissioning R&D Program
South Korea has allocated significant resources to research and development in nuclear decommissioning technologies and methodologies.

Innovative and Advanced Nuclear Reactor Decommissioning (IAND) Program (USA)
This program by the U.S. DOE focuses on developing advanced technologies for the decommissioning of nuclear reactors.

Nuclear Energy Agency (NEA) - Committee on Decommissioning of Nuclear Installations (CoDNI)
The NEA provides a platform for member countries to share knowledge and collaborate on decommissioning projects, facilitating the exchange of innovative approaches.

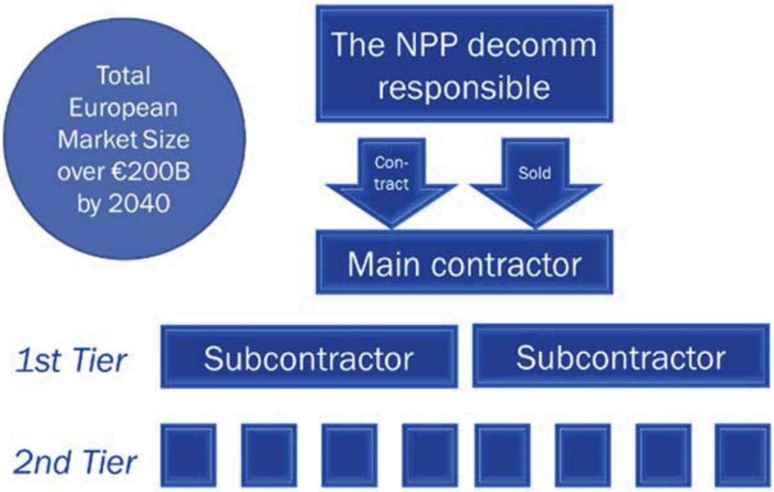

Figure 16. Hierarchy of nuclear decommissioning project management

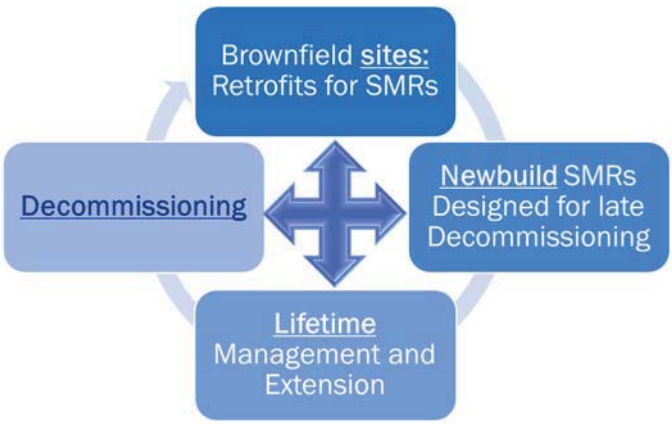

Figure 17. Nuclear power plant lifetime phases relevant for decommissioning service providers

4.3 Different reactor types

One decommissioning project contains a wide variety of subcontracting, product and service procurement, and hiring. It is a long-term project with parallel activities and separate contracts based on public tendering. The responsibilities and requirements for the main contractor are quite different from those of the second or third tier subcontractor and so are also the value of the contract and sales channels. Therefor the business opportunities over the lifespan of the project vary.

There are nowadays several different reactor types but historically two most common in civilian use in Europe are listed here with their main characteristics.

Pressurized Water Reactor (PWR)

Coolant:	Uses water both as a coolant and a moderator.
Pressure:	Operates at high pressure to prevent water from boiling.
Fuel:	Enriched uranium fuel rods.
Containment:	Large, robust containment structure to contain any potential leaks.
Example:	Ignalina Nuclear Power Plant (INPP), Lithuania Zwentendorf Nuclear Power Plant, Austria In preserved state, never operated for power production due to a public referendum.

Boiling Water Reactor (BWR)

Coolant:	Uses water that boils in the reactor core to produce steam, which then drives turbines.
Pressure:	Operates at lower pressure compared to PWRs.
Fuel:	Enriched uranium fuel rods.
Containment:	Generally, has a smaller containment structure than PWRs.
Examples:	Stade Nuclear Power Plant, Germany Barsebäck Nuclear Power Plant, Sweden

Figure 18. Boron neutron capture therapy (BNCT) station's structures under decommissioning at the FiR 1 research reactor.

5 Decommissioning risks and human factors

Understanding the hazards and risks of nuclear decommissioning is necessary for risk management in decommissioning projects. The factor that sets the decommissioning of nuclear facilities apart from the decommissioning of other industrial facilities (say, chemical plants or coal power plants) is the presence of significant amounts of radionuclides in the plant and often also in other parts of the site. These may generate amounts of ionizing radiation that are dangerous or even life-threatening to people exposed to them, and harm also other lifeforms.

Figure 19. Drilling of activated concrete samples from the biological shield of the FiR 1 research reactor.

The main part of risk-related work carried out in dECOmm consisted of two activities: identification of nuclear decommissioning related hazards and risks, and construction of a risk ontology for nuclear decommissioning. Hazard and risk analyses of nuclear decommissioning were put into regulatory context: certain risk analyses are required by nuclear or environmental regulators. Human factors-related work was carried out in two ways. The first consisted of expert interviews on general aspects related to decommissioning and the role of human factors in it. The second consisted of a literature review on human factors in decommissioning.

5.1 An overview of hazards and risks related to nuclear facility decommissioning

To understand risks involved in nuclear decommissioning, and the hazards, we look at various actors in the decommissioning process and people who might be affected by it. The license holder of the site to be decommissioned is responsible for the decommissioning but is rarely the company that will carry it out. Instead, it procures one or more contractors that do parts or all the decommissioning work. One of these may be a main contractor with whom the license holder makes a contract, and others may be subcontractors. Employees of the license holder may be present at the site during decommissioning, and certainly workers of the contractors will be present at different phases of the decommissioning. People who live so close to the site that radionuclides in a plume or water leak from the site could reach them through one pathway or another may also be affected by the realization of safety risks. Finally, there is the question who or what is affected if damage to the environment is caused by decommissioning; it is hard to name a specific party affected, so we call the party affected ‘nature’. Table 2 summarizes the types of risks and those affected by the realization of them.

Table 2. Types of risks involved in decommissioning and parties potentially affected by their realization.

Risk type	**Exposed parties**	**Notes**
Safety risks: occupational accidents and diseases	On-site workers of license holder and contractors	Types of occupational accidents are largely those of any construction/demolition work. The only exception is exposure to ionizing radiation, typically not present in conventional construction or demolition.
Safety risks: releases of harmful substances	On-site workers of license holder and contractors. People living or staying sufficiently close to the site	Solvents, waste oil, and other hazardous substances may be on site as relics of the plant’s earlier lifecycle phases. Some, such as solvents for decontamination, may have been brought on site to aid decommissioning. Hazardous substances may be accidentally released.
Safety risks: exposure to ionizing radiation	Workers of license holder and contractors; people living or staying sufficiently close to the site	Workers are exposed to ionizing radiation through ground shine from contaminated surfaces, ground shine from contaminated dust, inhalation of contaminated dust etc. If there is a liquid or gaseous release of substances containing radionuclides, people close to the site may be exposed to ionizing radiation through cloud shine, ground shine, inhalation, ingestion, and skin contact.
Project risks	License holder; contractors	Exceedance of project schedule or budget limits may bring extra cost to the companies involved. Also, substandard work or otherwise not achieving some decommissioning objectives may bring extra cost, but they may also jeopardize worker or public safety, and environmental values.

5.1.1 Decommissioning hazards

Nuclear decommissioning hazards may be categorized on several grounds. One categorization is based on the point of origin of the hazard. Some hazards, for example equipment failure, originate within the decommissioning site; these are called internal hazards. Others, such as lightning or terrorist attacks, originate from beyond the site; these are called external hazards. Some hazards may originate either from within the site or outside of it; examples include fire and flood.

Another categorization refers to the source of the hazard: hazards are either man-made or of natural origin. The latter is the categorization used in the ontology. This categorization principle has the justification that in the case of human-made hazards, there are ways to reduce the probability of hazard realization by addressing the root causes of the hazard; for example, the possibility of human error can be reduced by selecting workers conducting safety-critical tasks more carefully, training them better, equipping them appropriately, formulating solid work procedures etc. With natural hazards, there usually is no way to address its root causes effectively.

Figure 20. Lead blankets are widely used as a quick way to set up shielding for the dismantling of activated components.

5.1.2 Decommissioning risks

A more detailed description of the risk can be made by subjects and risk category:

- Public health and safety risks. During decommissioning, health and safety risks to the general public remain small after the removal of nuclear fuel; there is still a small inventory of radionuclides in the facility, and if a significant portion of this is released, it may cause health risks to the most affected individuals. Fires and handling of contaminated soil may release significant amounts of radionuclides. One cannot rule out the possibility that some poisonous substances (solvents used in decontamination, lead) are released to the environment as part of aquatic release, and part of this release may end up in drinking or irrigation water, causing health risks to drinkers of the water and eaters of irrigated crop. However, these risks are most likely small.

- Occupational health and safety risks to the decommissioning workers remain a factor to be considered for the whole decommissioning lifecycle. There are many hazards in a nuclear facility that induce health and safety risks. During dismantlement and demolition, ordinary industrial accidents may occur, for example because of collapse of structures or falling of heavy objects. Contaminated structures and equipment may have enough radionuclides on or inside for dangerous amounts of ionizing radiation to unprotected workers, for example through inhalation of radioactive aerosols produced in cutting and grinding. Fires and explosions may induce deaths, disability, harm, and damage and loss of property. Toxic or otherwise hazardous materials such as asbestos (still found in old nuclear facilities) and lead (used in paints, counterweights, and radiation shields) impose risks of poisoning and other health issues. Electric hazards are potential sources of electrical shock and fires. Natural hazards bring with them health and safety risks, and the risk of damage or loss of property.
- Environmental risks. Depending on the case, the consequences of the realization of environmental risks fall mainly on nature, the public, or the companies involved in decommissioning. The main environmental risks are involved with contamination of soil or water systems. Contaminants may include radionuclides and poisonous or otherwise harmful substances. Even before decommissioning, contamination of land or water systems may have occurred accidentally. Decontamination of contaminated soil is often possible, but tedious and costly. Decontamination of water systems is usually impracticable, and in that case, contamination leads to usage restrictions.
- Project risks. Arguably, the main project hazards are badly formulated contracts and poor planning, but also accidents and natural hazards play a role. The main project risks are that there is significant delay in project schedule (schedule risk), that the outcome of the project does not meet its specifications (performance risk), and that the cost of the project exceeds some given limit (cost risk). In the case of nuclear decommissioning, the realization of project risks mainly falls on the companies involved in the decommissioning project (the company or other organization that owns the site, contractors and subcontractors used in decommissioning). Due to the long timespans involved in nuclear decommissioning, it seems unlikely that serious schedule risks would be realized during the decommissioning lifecycle.

However, cost risks could be realized due to uncertainties related to the site itself and the long timespans involved. Performance risks could be related to for example contaminated land masses that could prevent the release of the site to unrestricted use at least in a reasonable time frame. Some of the negative consequences may fall on the government or society; this may happen for example if the site owner goes bankrupt. The realization of any other risk, or any other abnormal events during the decommissioning lifecycle, may contribute to project risks; also, human errors contribute to project risks, as well as defective project planning.

5.2 Decommissioning risk analysis institutional context

5.2.1 Regulation

Environmental impact assessment of nuclear power stations and reactors is required by directives 2011/92 and 2014/52 of European Union. The directives apply to decommissioning until all nuclear fuel and radioactively contaminated elements have been removed. Among other things, the directives require consideration of the probability of an environmental impact indicating that some sort of risk assessment is needed. Finnish act on environmental impact assessment procedure 252/2017 includes a similar requirement.

Finnish YVL guide for nuclear safety sets several requirements for the risk analysis of decommissioning. Probabilistic risk assessment is required for the risk of nuclear fuel damage until the fuel has been removed (YVL A.7). This covers all nuclear fuel handling procedures, transfers, and storage locations. The risk impact of decommissioning to other units at a nuclear power plant site needs to also be analysed. The risk assessment needs to be submitted to STUK well before the end of the nuclear reactor operation.

YVL D.4 requires that the radiation safety of workers and environment has to be demonstrated by deterministic analysis. Probabilistic assessment is required when the potential consequences are significant. Periodic safety reviews are required during decommissioning.

IAEA’s General safety requirement’s part 6 specifies general safety requirements for decommissioning. The decommissioning plan must be supported by safety assessment. A graded approach must be used in all aspects of decommissioning. More specific requirements/recommendations for the safety assessment can be found from IAEA’s Safety guide No. WS-G-5.2. All relevant hazards to workers, public and environment must be considered in the safety assessment, including radiation exposures, toxic and other dangerous materials, and industrial hazards. The nature, magnitude and likelihood of hazards must be evaluated systematically. Reduction in radiological hazards to be achieved by decommissioning must be quantified. Necessary safety measures, limit controls and conditions to ensure safety must be identified. In addition, the appendix of IAEA SSG-47 contains safety assessment requirements. Detailed safety assessment of a later decommissioning phase is not required before the beginning of the decommissioning but only before the beginning of the phase.

Finnish occupational safety and health act (738/2002) also requires systematic analysis of risks and hazards caused by the work, working hours, workspaces, other aspects of the working environment and working conditions.

Figure 21. Each radioactive waste component and container requires marking and documentation.

5.3 Risk analysis methods for decommissioning

Literature on decommissioning risk analysis methods is relatively scarce. The risk matrix technique is a typical qualitative method that has been applied in many fields and also proposed for decommissioning risk analysis (Jeong et al., 2010; Park et al., 2019). Fuzzy-based risk assessment is another method that has been proposed (Jeong et al., 2010; Kim et al., 2020). Fuzzy inference is seen as a good method for combined analysis of radiological and non-radiological hazards as it can combine qualitative and quantitative analyses.

Probabilistic risk assessment methods, such as event tree analysis and fault tree analysis, are needed for the analysis of major radiological accidents, such as spent fuel pool accidents, during decommissioning (Tian et al., 2018; U.S. NRC, 2001).

For occupational risk assessment outside the decommissioning context, commonly used methods are preliminary hazard analysis and checklists (Pinto et al., 2011). Also, bow-tie method (Ale et al., 2008) and risk score (Kokangul et al., 2017) have been applied. These methods seem well applicable to decommissioning. Many more complex methods have been considered in scientific literature (Pinto et al., 2011), but simpler methods are usually used in practice.

5.4 An ontology of decommissioning risks

A nuclear decommissioning risk ontology called NuDRisk was constructed in the dECOmm project. It may help decommissioning hazard and risk analyses in various ways: for example, by aiding in identifying a suitable risk analysis method for a given analysis, identifying parts of earlier analyses that can be reused based on commonalities, and supporting the decommissioning risk analysis process.

In an ontology, the concepts of a subject domain (in this case, nuclear decommissioning, its hazards and risks, and their analysis), their properties, and relations between them are represented, formally named, and described (for a more thorough treatment of various aspects of ontologies, see (Staab and Studer, 2009). NuDRisk consists of decommissioning activities, decommissioning agents (institutions such as regulators and companies, individuals such as decommissioning workers and former plant workers), hazards, decommissioning methods, risk analysis methods, risks, plant systems and structures, and decommissioning systems (includes equipment, means of communication, software etc. used in decommissioning).

5.4.1 Uses of risk ontology

The following uses have been identified for NuDRisk. As the ontology itself is a representation of knowledge relevant to decommissioning risks, processing is needed to implement the uses. The entity that conducts the processing is here called ontology system; it could be the ontology development system used (Protégé), a custom-made computer program, or humans that utilize the information contained in the ontology.

- find appropriate risk analysis methods for given risk analysis problem. The user gives features of the risk analysis problem (hazards considered, risk types considered, decommissioning activity/activities, decommissioning phase, and part of the facility). The ontology system utilizes this information, and the information contained in the ontology about information needs, possible uses of results, and application domain of each risk analysis method, to identify which methods are applicable to the problem.
- facilitate the use of a risk analysis method. The ontology system can help in finding appropriate and relevant data, identifying what different terms used in the nuclear decommissioning domain mean, and specifying what information is needed when using the method.
- help to recognize a risky situation. The ontology system may help in recognizing whether all the elements needed for the realization of a hazard – for example, air, flammable material, and an ignition source sufficiently close to the material.

- reuse earlier analyses. The ontology system may be used in recognizing similarities between the conditions in which a decommissioning risk analysis has been conducted earlier, and situation at hand. Then, appropriate parts of this earlier analysis may be utilized in the current situation.

5.5 Human factors and decommissioning phases

Compared with the other life cycle phases, decommissioning is a somewhat neglected one from the human factor's perspective. NUREG-0711 (O'Haraet al, 2012) presents a review model for human factors engineering as conceived by the nuclear regulatory commission of the United States. In the model, the reviewed matters are classified according to the phase of the life cycle of a nuclear power plant. The phases are (1) planning and analysis, (2) design, (3) verification and validation and (4) implementation and operation (Figure 22). Obviously, the last, decommissioning, phase is missing.

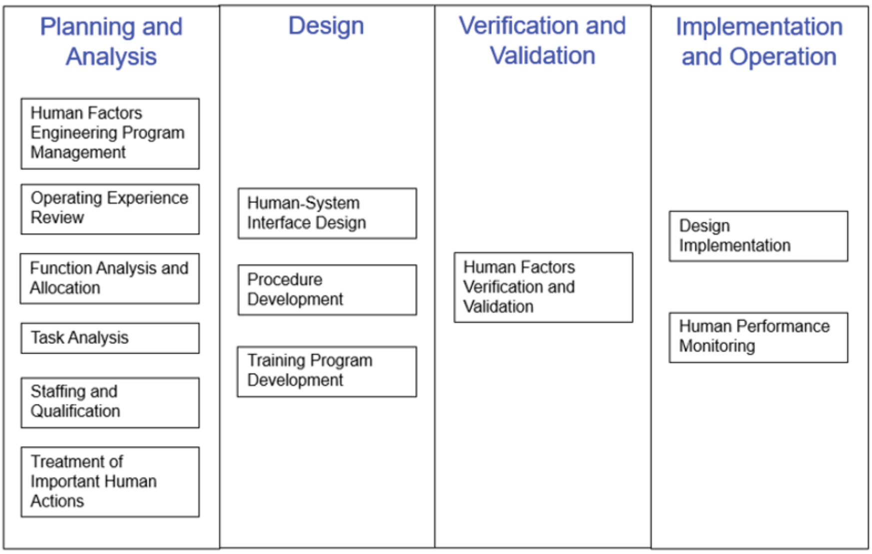

Figure 22. Elements of the human factors engineering (HFE) program review model, redrawn from NUREG-0711 rev. 3.

Decommissioning would be fifth phase of the life cycle of a nuclear power plant from the human factor's perspective. The reason for not having decommissioning included in the life cycle as presented by an American authority is probably the so far meagre need for dealing with decommissioning related human factors issues. This does not mean that the phase would be of less importance from human factors perspective. On the contrary, as the phase is composed of transient states (Owen et al., 2013) with new emerging challenges, decommissioning needs structured human factors approach to keep human error in minimum and performance and safety on as good a level as practically possible.

Decommissioning can be described briefly as "the suite of processes involved in withdrawing a facility from service at the end of its life; its deconstruction and dismantling; and the removal of components for reuse, remanufacturing, recycling, storage and/or disposal" (Invernizzi et al. 2020).

5.5.1 Interviews concerning decommissioning experiences of FiR 1

Interviews about the decommissioning experiences regarding the decommissioning of FiR 1, the Finnish research reactor of VTT were conducted among four professionals having a role in the decommissioning – the roles of owner, subcontractor doing most of the actual work, and Finnish nuclear regulator. During the interviews, the decommissioning was in the planning phase. The results highlighted the need for constant and smooth dialogue about plan revisions, regulatory demands and schedule changes between the different stakeholders. The accurate analysis of the results remains among the stakeholders.

5.5.2 Human factors elements in nuclear decommissioning

Above, the phases in the nuclear decommissioning are described so that the focus is on human tasks and challenges. Nuclear decommissioning can also be scrutinized from a human factor's perspective so that the critical human elements are elicited, in a way similar way to that presented in NUREG-0711 (O'Hara et al., 2012). There, the matters to review by the American regulator are located within the life-cycle model of a nuclear power plant. Based on this model, decommissioning has several HFE elements, like the other phases. They are:

- task analysis
- staffing and qualifications
- procedure development
- training development
- human performance monitoring.

5.5.2.1 Task analysis

Task analysis needs to be conducted in the planning phase of decommissioning, because the tasks are mainly different from the ones during the operating phase. The shutdown of the plant shares some similarities but in decommissioning, the reactor is controlled so that the radioactivity will not be raised again. This task belongs to the transitional phase between the operating plant and the plant undergoing decommissioning.

The tasks in nuclear decommissioning are related to demolition, waste management and spent fuel management. These tasks are unique and must be performed appropriately and safely, without causing occupational injuries. Only some tasks, such as classifying and reporting nuclear waste items, are repeated in a similar manner during decommissioning. Thus, the tasks must be analysed and synthesized with great care.

5.5.2.2 Staffing and qualifications

Personnel does not stay the same when the end of the operational phase is approaching. Part of personnel seek for other work, not being willing to stay in the plant without a future. Decommissioning also requires new types of professionals as demolition is not among the competences of personnel of an operating nuclear power plant. Thus, subcontractors are needed. The roles and the number of the role representatives to work in the decommissioning phase must be estimated and the needed competences, and means to verify them, must be specified.

5.5.2.3 Procedure development

Procedures are needed as the tasks in decommissioning are hardly familiar beforehand to personnel. Procedures should be clear and extensive but in a reasonable level. The adequacy of procedures needs to be verified and validated to ensure that they serve their purpose.

5.5.2.4 Training development

Training regarding radioactivity as well as occupational safety aspects is developed. Also, complex tasks require training so that the tasks can be accomplished without previous experience about them. Training should be clear and extensive but in a reasonable level. Efficient training methods should be used to ensure learning. The adequacy of training needs to be verified and validated to ensure that they serve their purpose.

5.5.2.5 Human performance monitoring

Human performance monitoring is conducted to ensure that no significant safety degradation takes place due to the changes made in the plant, just like in the operational phase (O'Hara et al., 2012). Monitoring pertains especially to the definition and following an appropriate way of reporting, documenting, and communicating relevant matters in an efficient way, as well as to task accomplishment.

5.5.2.6 The most important management tasks

Decommissioning can also be scrutinized from the management point of view. Management is a type of activity that typically belongs in hierarchy to higher organizational levels than the ones of workers and their immediate superiors. However, in the context of this document, management is considered as something belonging to all levels of personnel hierarchy. Then, the most important human factors elements can be limited to three different types of management tasks (Figure 23):

- Change management
- Safety management
- Competence management

Figure 23. The critical management tasks in decommissioning.

5.5.2.7 Change management

Change management is different in an operational organization than in a nuclear power plant in the decommissioning phase. In a nuclear power plant approaching decommissioning, there is for instance no need to motivate personnel about the need to change, as decommissioning is characterized by constant change. Instead, change management is needed because there are not many routines as the object of work and the work environment is constantly changing. Thus, effective change management is a prerequisite for a successful decommissioning.

Change management includes planning for changes, enabling the identification of change and the high-level measures to handle it, and flexibility to changes. It requires effective communication, which is important in all levels and directions. Communication must be clear and open when working with colleagues for a common goal such as planning or working in pairs at the site, so that anomalies and changes are noticed and considered in work. Clear and open communication is also needed between different levels of hierarchy so that everybody is informed about the objectives and how the work is proceeding relative to plans, towards the predefined objectives. Clear and open communication is also needed between the licensee and the nuclear regulator to ensure safe proceeding of the decommissioning project.

5.5.2.8 Safety management

The importance of safety is characteristic of the nuclear domain. Safety management means safety supporting activities in all levels – in planning, in work activities, and in opinions and attitudes. In the last case, safety means that it is valued throughout all decommissioning related decisions and activities. Basically, safety is equally important in all phases of a nuclear power plant lifecycle. It is, however, more demanding in decommissioning, because the work is transient by nature, changing in the same pace as decommissioning proceeds - safety systems, structures, components, and people serving safety may all change during the transition from one state to another (Owen et al., 2013). This means that new hazards might emerge (IAEA, 2018), despite careful and professional-level planning. Even if this challenge is mitigated by the fact that safety risks are reduced in decommissioning (IAEA, 2004), hazards need to be addressed properly, enabled by daily briefings and feedback sessions (IAEA, 2018) as well as by safety-supporting plans pertaining to all decommissioning work.

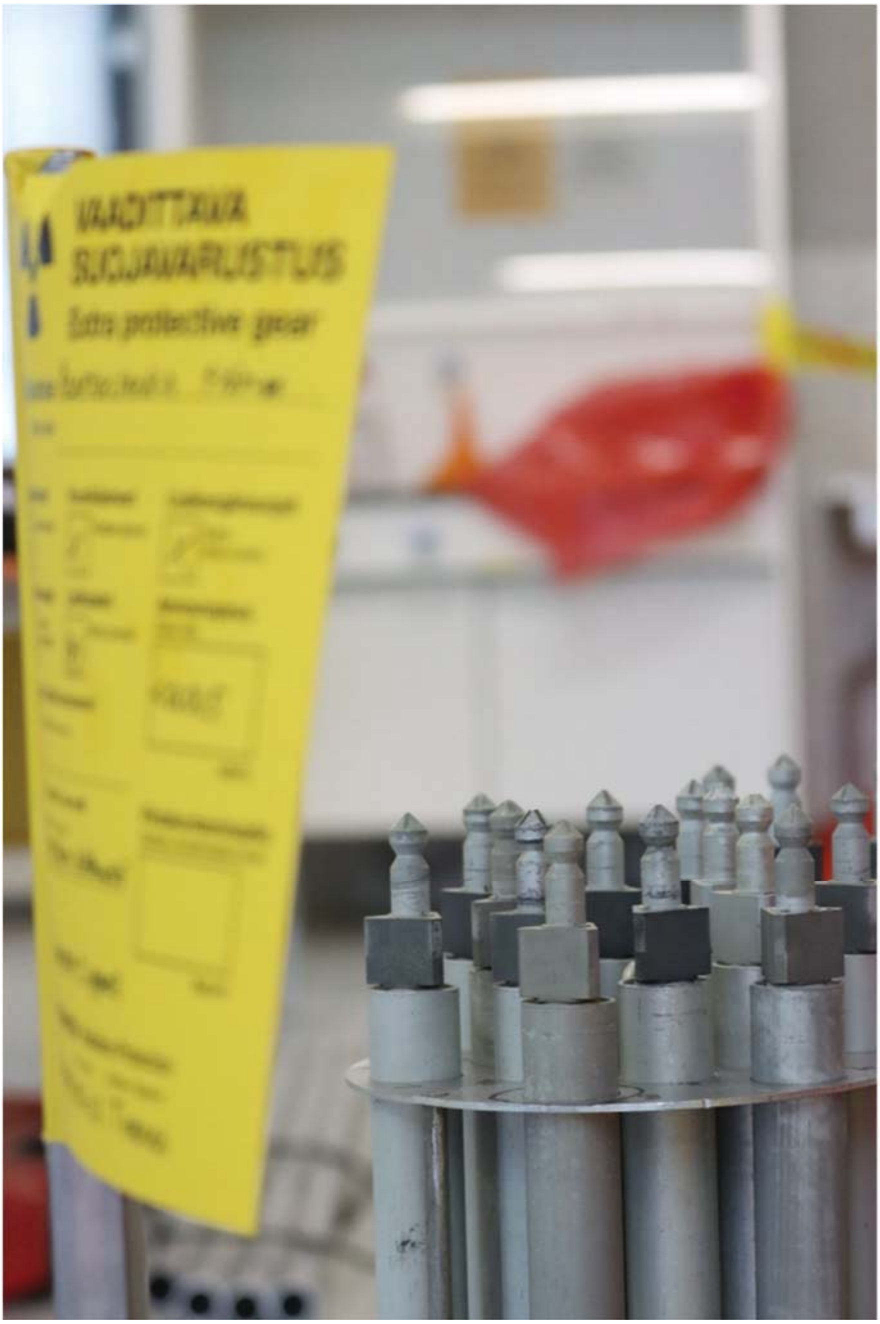

Figure 24. Some of used reactor components are classified as dual-use items (other nuclear material) while they are also forming different types of radioactive waste. During decommissioning, the maintenance of the facility's nuclear materials inventory bookkeeping requires special attention and close communication with the regulator and nuclear safeguards organizations. Graphite elements used in the core of the FiR 1 research reactor are an example.

6 The Finnish Research Reactor FiR 1 as a Case Study

6.1 Description of the reactor and status of decommissioning

Finland's only research reactor FiR 1, a 250 kW TRIGA Mk II open-tank reactor, was operated from March 1962 until its permanent shutdown in June 2015 (see Figure 25). The reactor is now defueled and in a permanent shutdown state, the technical maintenance and security surveillance of the reactor and the premises continuing. In June 2021, the Government of Finland granted to VTT (the licensee of FiR 1) Finland's first nuclear decommissioning licence. Preparations for decommissioning have been just completed, and radioactive dismantling tasks are starting in May–June 2023. In June 2021, the Government of Finland granted, following the Nuclear Energy Act [Nuclear Energy Act 1987], Finland's first nuclear decommissioning licence to the operator, VTT Technical Research Centre of Finland Ltd, for decommissioning FiR 1.

Figure 25. Reactor operator just about to shut down FiR 1 for the last time on 30 June 2015. At the end of the same year, the core was made permanently subcritical by removing enough fuel elements.

In this Case Study, we will (i) review the activities performed prior to decommissioning in the design, operation, and maintenance of FiR 1, including spent fuel management; (ii) describe the reactor's technical characteristics, past activities, and radioactive inventories; (iii) review the organizational and management activities between shutdown and decommissioning; and (iv) review VTT's experiences and lessons learned concerning the decommissioning.

6.1.1 Shipping of FiR 1 irradiated fuel for re-use in the United States

During the operation of the FiR 1 reactor in Finland from 1962 to 2015, a total of 103 elements of irradiated fuel were generated, comprising approximately 15 kg of uranium, including 3 kg of ^{235}U. Originally, the plan was to return the fuel to the United States as part of the US DOE's return program, which had an initial expiration date set for May 2019. However, just before its expiry, the program was extended to May 2029. The intended destination for the fuel was the Idaho National Laboratory (INL) in the USA, where similar batches of nuclear fuel from TRIGA research reactors had been previously returned from various countries.

The fuel return program to the INL had been halted since 2014 due to the blocking of nuclear waste transports by the state of Idaho, citing breaches of the Idaho Settlement Agreement. This long-standing challenge posed a significant obstacle for VTT in planning, licensing, and contracting subsequent phases of decommissioning, as the removal of fuel from the site was a crucial step.

Figure 26. Operators preparing radiation shields for handling dry spent fuel in the FiR 1 reactor hall in 2020.

Despite the primary option being the US return, VTT had also maintained a secondary option of final disposal in Finland. However, this alternative would have required additional licensing for the encapsulation and disposal facilities, which are currently being constructed by Posiva in Olkiluoto on the western coast of Finland.

In July 2020, the U.S. Geological Survey (USGS) in Denver, Colorado, approached VTT and expressed their need for additional fuel to continue operating their reactor. Since suitable fuel production had been suspended for several years and was not available on the market, it was mutually beneficial for both parties to transfer the used FiR 1 fuel to the USGS for further use in their reactor. The remaining fuel had a significant utility value, with a maximum burnup of approximately 24 %. The United States Department of Energy will be responsible for the fuel once it reaches the end of its useful life.

In November 2020, a contract for the supply of the used fuel was established, and VTT arranged for the safe international transport of the fuel from Espoo, Finland to the USGS with the support of Edlow International Company. The transportation process, involving both road and sea transport, was closely supervised by STUK and regulatory and safety authorities in the USA. In January 2021, the USGS received all the irradiated fuel from the FiR 1 reactor.

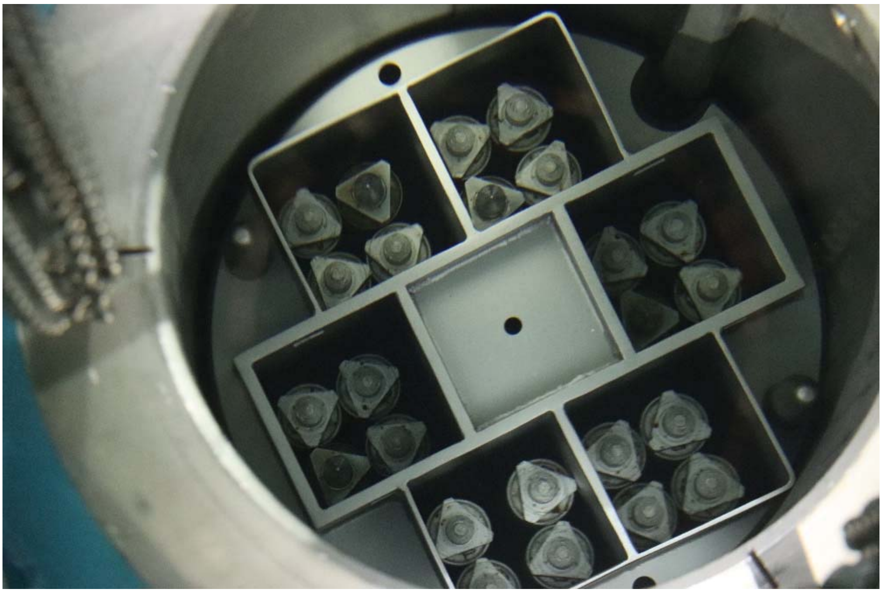

Figure 27. *FiR 1 fuel elements packed into an inner basket of a massive transport cask. The photo is from the reactor pool, where water provides an effective shielding against radiation.*

It is worth noting that the arrangement for cooperative international spent fuel management abroad is an exception permitted by the Finnish Nuclear Energy Act. Prior to sending the fuel abroad, Finland received a report from the US authorities confirming their commitment to managing the fuel batch. It is planned that once the USGS ceases to use its reactor, all of its irradiated fuel will be delivered to the Idaho National Laboratory (INL).

6.2 Regulatory and licensing requirements

6.2.1 Generic international requirements

In many countries, the regulatory framework for nuclear and radiation legislation involves a set of interconnected components. Typically, there is a primary legislative act, such as a Nuclear Energy Act, which establishes the legal foundation for the use of nuclear energy and governs the operation of nuclear facilities. Supporting the primary act, there may be additional regulations and decrees that provide more detailed requirements and specifications, covering aspects such as licensing, safety standards, waste management, and radiation protection.

The regulatory authority responsible for overseeing compliance with these laws and regulations is typically an independent organization or agency. This regulatory authority plays a crucial role in ensuring the safe and secure use of nuclear energy and the protection of individuals and the environment from radiation hazards. It monitors and enforces compliance with regulations, conducts inspections and assessments, and grants licenses for the operation of nuclear facilities.
To further specify technical and safety requirements, regulatory authorities often develop guides, handbooks, or codes of practice. These documents provide detailed instructions and guidelines for various aspects of nuclear and radiation

Figure 28. Radioactive waste streams require licensed waste management chains.

safety, such as design criteria, operational procedures, and emergency preparedness. These guidance documents help ensure consistency and best practices across the industry.

Additionally, government ministries or departments often have roles related to nuclear and radiation legislation. These ministries may include energy, environment, health, or labour ministries, among others, depending on the specific jurisdiction. Their responsibilities typically involve policymaking, coordination, and implementation of laws and regulations related to nuclear energy, safety, environmental protection, and public health.

International organizations IAEA and OECD NEA collaborate closely with their member countries to foster the exchange of information, knowledge, and expertise. They provide platforms for international cooperation, encourage the harmonization of standards and practices, and support capacity-building efforts in countries seeking to develop or expand their nuclear energy programs. These organizations also serve as forums for addressing emerging challenges, promoting research and development, and facilitating dialogue and collaboration among member states, industry stakeholders, and other international organizations.

Overall, the international regulatory framework for nuclear and radiation legislation involves the interaction and interdependence of legislative acts, regulations, regulatory authorities, guidance documents, and government ministries. This comprehensive approach aims to ensure the safe, secure, and responsible use of nuclear energy while protecting human health, the environment, and public well-being. While the specific structures and entities may vary between countries, the overarching goal remains consistent: to establish and maintain effective regulations that safeguard society throughout all aspects of nuclear and radiation activities.

6.2.2 Specific for Finland

In Finland, the regulatory framework for nuclear and radiation legislation involves several key components and entities. The Nuclear Energy Act serves as the overarching legislation, providing the legal framework for the use of nuclear energy and the regulation of nuclear facilities. The Nuclear Energy Decree supplements the Act by specifying detailed regulations and requirements related to various aspects of nuclear energy, such as licensing, safety, and waste management. The Radiation Act, on the other hand, focuses on radiation safety and protection, addressing the use of ionizing radiation in various applications. The Finnish Radiation and Nuclear Safety Authority (STUK) plays a crucial role as the regulatory authority responsible for overseeing and enforcing compliance with these laws and regulations. STUK issues specific regulations known as STUK Regulations, and issues so-called YVL guides, which provide detailed non-binding instructions and guidelines for nuclear and radiation safety in various technical areas. Furthermore, various government ministries, such as the Ministry of Economic Affairs and Employment, Ministry of the Environment, and Ministry of Social Affairs and Health, have specific roles in nuclear and radiation legislation, ensuring the coordination and implementation of policies related to nuclear energy, safety, environmental protection, and public health. These ministries work in tandem with STUK to ensure the effective and comprehensive regulation of nuclear and radiation activities in Finland, promoting safety, environmental sustainability, and public well-being.

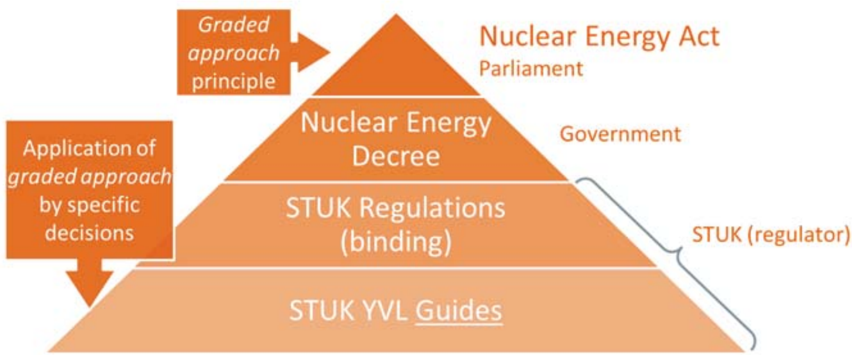

Figure 29. Four levels of nuclear energy regulation in Finland. Concerning FiR 1 as a low-risk nuclear facility, the **graded approach** is extremely relevant. The principle is defined in the Act, and it is applied in practice by specific decisions of STUK.

In the following, we summarize the main steps towards fulfilling the prerequisites for the two licences (nuclear licence for FiR 1 and radiation safety licence for OK3). The main prerequisite is that the safety of operations as well as the personnel and financial capacity of the applicant shall be proven to be sufficient. In particular, **the methods available to the applicant for the decommissioning of the nuclear facility as well as other nuclear waste management shall be adequate and appropriate** (quoting the Nuclear Energy Act). The Radiation Act sets very similar requirements for the applicant as the Nuclear Energy Act. E.g., the waste inventory of the laboratory was estimated during the licensing process.

6.2.3 Specific for FiR 1

The FiR 1 research reactor was characterized during operations by its location in the middle of a university campus and on the other hand by its low thermal power, excellent passive safety features, and a relatively small radioactive inventory. It is very justified to classify FiR 1 as a low-risk nuclear facility while paying attention to its exceptional location (more than 17 000 people during daytime within just 500 m radius around the facility). These characteristics are valid also during decommissioning and must be accounted for in radiation safety planning, risk analyses, security measures, and emergency and communication preparations.

Figure 30. The reactor building looks like a normal office from outside.

Another specific feature is the fact that VTT is renting the reactor building from Aalto University Campus and Real Estate (ACRE) and will return it to the owner after decommissioning and clearance from regulatory control are completed. This is one type of **green field** end state, although the building will remain and be used for other purposes by the university or some other next tenant. One should understand the meaning of **”green field”** here as “**no restrictions for further use”** of the building, or **“unconditional clearance”**. In contrast, **“brown field”** end state would mean **“conditional clearance”** with some case-specific conditions for further use, for instance allowing only industrial activities but no kindergarten or cafeteria to be established in the building or in the area.

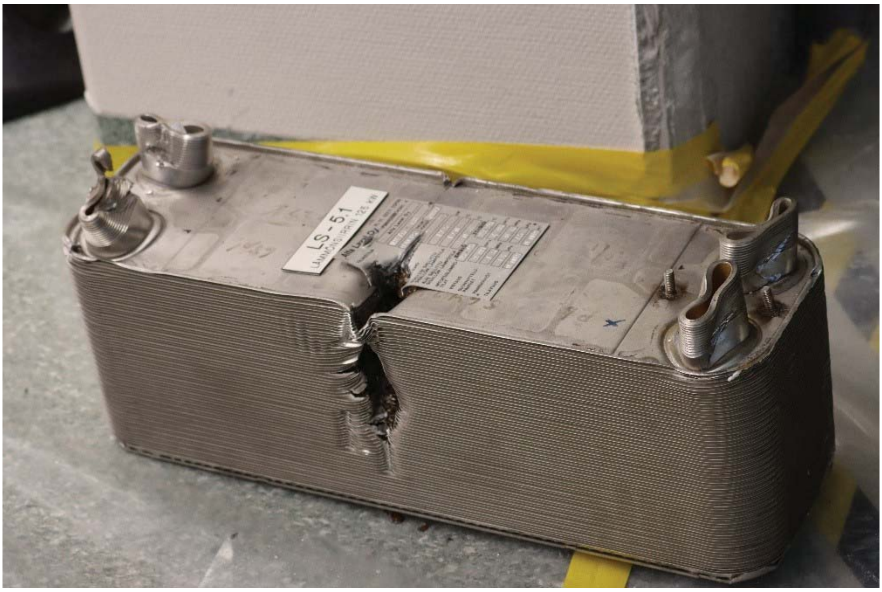

Figure 31. Some of used reactor components are classified as dual-use items (other nuclear material) while they are also forming different types of radioactive waste. During decommissioning, the maintenance of the facility's nuclear materials inventory bookkeeping requires special attention and close communication with the regulator and nuclear safeguards organizations. The small heat exchangers of the FiR 1 research reactor are another example.

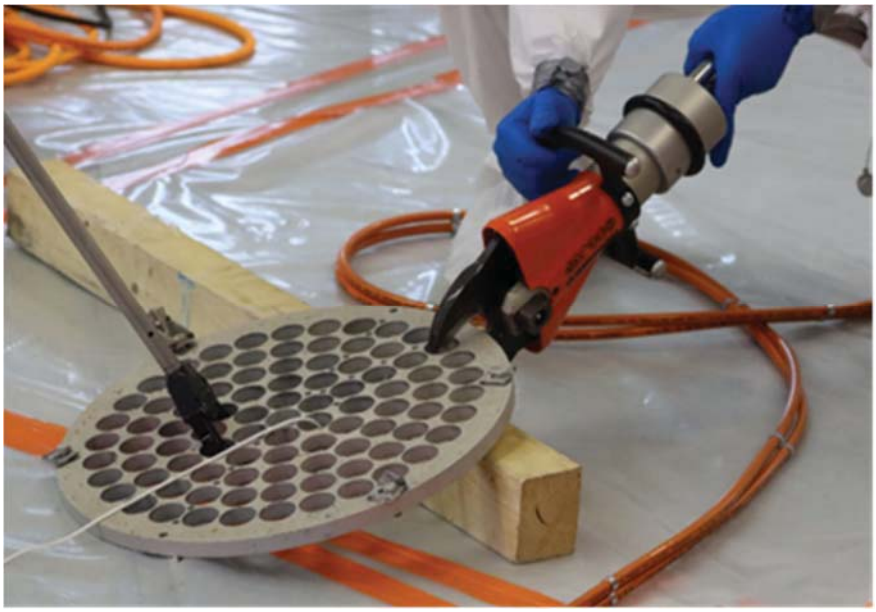

Figure 32. Some of used reactor components are classified as dual-use items (other nuclear material) while they are also forming different types of radioactive waste. During decommissioning, the maintenance of the facility's nuclear materials inventory bookkeeping requires special attention and close communication with the regulator and nuclear safeguards organizations. The core grid plate of the FiR 1 research reactor is another example.

6.3 Decommissioning contracting and supply chain management

Typically, a significant share of work is outsourced by the license holder of a nuclear facility under decommissioning. In fact, implementation contracts can be the main tool to for decommissioning project execution and, therefore, they bring major implications to project management, licensing, funding etc.

During the specific session on the IAEA workshop[1] special consideration was given to the impacts that contract strategy selection has on the Owner / Client organization: *"A good contract strategy will improve supply chain management whilst ensuring delivery for the Owner / Client at maximum value and minimal cost. In addition, a good contract strategy will support the delivery of best practice for the client and, if applicable, enable innovation from the subject matter experts engaged under the contract."*

There are many factors that may influence the selection of a contract; one key factor is the intended allocation of risk. A fixed-price contract will result in most of the risk being taken by the contractor, whereas a basic time and materials contract means that the owner or client bears most of the risk. The Owner / Client can only transfer certain risks to the supply chain and, ultimately, they will always be responsible for the satisfactory implementation of decommissioning and therefore cannot reallocate the associated risk.

[1] IAEA International Workshop on Preparing for Implementation of Decommissioning of Nuclear Facilities, Tsuruga, Japan, 2019

The contract strategy will also have a significant impact on the design of the organizational structure for project delivery required by the Owner / Client organization and how they intend to manage the knowledge gained during the project.

A fixed-price contract will result in an organization that can provide oversight of the contract with a smaller team having contract management experience. A cost reimbursable contract may facilitate a more collaborative approach to delivery with the client and contractor organizations working together towards a common goal.

Figure 33. Activity measurements are done constantly to ensure right waste characterization and safe working methods.

6.3.1 Regulation pertaining to supply chain management

Generic requirements set out by the IAEA for supply chain management in the use of nuclear energy (without a specific reference to decommissioning) are [IAEA, 2016]:

The organization shall put in place arrangements with vendors, contractors and suppliers for specifying, monitoring and managing the supply to it of items, products and services that may influence safety.

4.33. The organization shall retain responsibility for safety when contracting out any processes and when receiving any item, product or service in the supply chain[2].

4.34. The organization shall have a clear understanding and knowledge of the product or service being supplied[3]. The organization shall itself retain the

[2] The supply chain, described as ‘suppliers’, typically includes designers, vendors, manufacturers and constructors, employers, contractors, subcontractors, and consigners and carriers who supply safety related items. The supply chain can also include other parts of the organization and parent organizations.

[3] The capability of the organization to have a clear understanding and knowledge of the product or service to be supplied is sometimes termed an ‘informed customer’ capability.

competence to specify the scope and standard of a required product or service, and subsequently to assess whether the product or service supplied meets the applicable safety requirements.

4.35. The management system shall include arrangements for qualification, selection, evaluation, procurement, and oversight of the supply chain.

4.36. The organization shall make arrangements for ensuring that suppliers of items, products and services important to safety adhere to safety requirements and meet the organization's expectations of safe conduct in their delivery.

Regulating safety is a national responsibility, and many countries have adopted the IAEA's standards for use in their national regulations. For instance, in Finland, the Nuclear Energy Act reinforces these principles:

The licence holder shall be under an obligation to ensure the safe use of nuclear energy. This obligation may not be delegated to another party. The licence holder shall ensure that the products and services of contractors and subcontractors which affect the nuclear safety of the nuclear facility meet the requirements of this Act. [Section 9 of Nuclear Energy Act]

Furthermore, following the regulatory structure applied in Finland, more detailed requirements set by the nuclear regulator. However, concerning supplier management, the content of this requirement is essentially the same as in the Act:

The licensee shall commit and oblige its employees and the suppliers and subcontractors whose involvement affects the safety of the nuclear facility to adhere to the systematic management of safety and quality. [STUK Y/1/2018].

Finally, on the lowest (most technical) level of regulation, there are many guidelines issued by the regulator – in particular, relevant in this context are guides YVL A.3, YVL A.4, and YVL D.4 [STUK 2019, 2020a, 2020b]. These guidelines are non-binding in the sense that the licensee can always propose an alternative way to fulfil the goal of a single requirement, if the achieved safety level is at least as high. A number of specific requirements in the above-mentioned guides reiterate the responsibility of the licensee to ensure the suppliers' ability to act safely in the same manner as the staff of the licensee. E.g., YVL A.3, requirement 402 states:

"The licensee is obliged to ensure that the regulatory requirements and guides are complied with. This shall also be taken into account during the procurement of products and services having a bearing on the nuclear and radiation safety of the nuclear facility. It shall be ensured that organizations contributing to the plant delivery or plant modifications understand and comply with the delivery-related requirements. The licensee shall communicate the requirements to the product suppliers by contractual means (contract documents) and ensure and control the fulfilment of the requirements throughout the supply chain."

Any supply contract starts with a procurement procedure executed by the contracting body. Here, not only safety concerns set the boundary conditions for contracting, but there is additional legislation concerning procurement, especially public procurements. The selection of the most suitable procedure depends on the clarity/complexity of the scope and on the availability of existing solutions for the purpose. For instance, in the case of unique or rare reactor types to be decommissioned, the dismantling techniques or waste management solutions may require significant additional development. To attract tenderers to offer services in such cases, additional incentive can be provided to them by selecting a procurement procedure that includes an element of development.

In case of public contracting bodies, or other bodies operating on public funding, their procurements are usually subject to rules aiming at producing best value for the use of public funds. On EU level, the directive 2014/24/EU on public procurement defines the boundaries within which the EU Member States can implement their respective national legislation on public procurements.

The more complex the scope of the procurement, the more important it is to allocate sufficient time and expertise both in the substance matter and procurements in order to achieve a good contract, which forms the basis for a working relationship with the supplier. The best competence on decommissioning is likely to lie at the suppliers' side and can be utilized for mutual benefit in the procurement by selecting a participatory procurement procedure (e.g., competitive procedure with negotiation, competitive dialogue, or innovation partnership, see Table 7-1).

Table 7-1. Procurement procedures according to the EU directive 2014/24/EU.

Procurement procedure	Participation and selection of participants	Prerequisites for application	Benefits	Challenges
Open procedure	Any interested economic operator may submit a tender in response to a call for competition.	The "default" procedure – no specific prerequisites.	Most straightforward procedure with shortest minimum time to complete procurement.	Scope must be clearly defined by the contracting body for fair and transparent comparison of tenders.
Restricted procedure	Any economic operator may submit a request to participate in response to a call for competition […] by providing the information for qualitative selection that is requested by the contracting authority.	Applicable e.g., if the contracting authority wishes to limit the number of tenderers, or in cases in which technical specifications contain sensitive information, (request to participate includes signed NDA).	Helps limiting the number of tenders to be compared (savings in work). Better control of information than in open procedure.	Two-step procedure: increases the minimum time to complete procurement.
Competitive procedure with negotiation	Same as above.	Needs of the contracting authority cannot be met without adaptation of readily available solutions. Scope of contract includes design or innovative solutions. Prior negotiations are necessary because of specific circumstances related to the nature, the complexity or the legal and financial make-up or because of the risks attaching to them.	Brings together the knowledge and boundary conditions from all potential tenderers. Can improve significantly the quality of the final Call for Tenders. Competitive nature of tendering is preserved.	Significantly longer process than open or restricted procedure (several phases, more work and time). Requires careful adaptation of the Terms of Reference between negotiations and launching of final Call for Tenders. Attention to be paid to equal treatment of tenderers.
Competitive dialogue	Any economic operator may submit a request to participate in response to a contract notice by providing the information for qualitative selection that is requested by the contracting authority.	Same as above.	Compared to the above, additional freedom for the tenderer to offer their own optimal solutions. Tenderers can be compensated for their efforts. Competitive nature of tendering is preserved.	Attention to be paid not to reveal to the other participants solutions proposed or other confidential information communicated by a tenderer.
Innovation partnership	Same as above.	Development and purchase of an innovative product, service or works that cannot be met by purchasing products, services or works already available on the market.	Provides a framework and an opportunity for a broad partnership. Tenderers can be compensated for their efforts. Helps attracting tenderers (innovation partners) to develop solutions by lowering their risk. Competitive nature of tendering is preserved.	Little experience on the use of the procedure so far. Uncertainty on the result. Requires correct description of the needs. Additional costs from the compensation of development in case of several innovation partners. Contract conditions, including IPR questions.
(Negotiated procedure without prior publication)	The Directive allows EU Member States to implement on their national legislation a negotiated procedure without prior publication of a call for competition, to be applied in specific cases and circumstances.			

Privately owned operators have generally more freedom in selecting the method they prefer using in procurements. While they can avoid some of the formalism related to public procurements, the goal is the same: Achieve best value for shareholder money.

6.3.2 Implementation of supply chain management in operator's management system

Certified quality and environmental management system of a nuclear operator provides a solid basis for the management of the supply chain also in nuclear projects. In practice, similar certifications are required from the suppliers and subcontractors. In addition, reflecting the requirements reviewed in Section 6.3.1, it is practically mandatory that the suppliers and their subcontractors work under complete control of the licensee's organization as regards nuclear and radiation safety. Typically, the internal rules and regulations of the nuclear facility define those additional practices, and these rules and regulations must be approved by the nuclear regulator. There must be a clearly defined responsibility for one or several managerial position in the licensee's organization to ensure that suppliers and their subcontractors fulfil all safety requirements and that their safety culture is high in general. It is obvious that these practices must be written out in the supply contracts, and brought up early during the procurement of services, to make sure that the suppliers and their subcontractors are well prepared already at the time of tendering.

6.3.3 Experiences/Case studies

In March 2020, VTT Technical Research Centre of Finland Ltd. (state-owned non-profit company, licensee and operator of the permanently shut down FiR 1 research reactor) awarded a contract on **decommissioning services for FiR 1 research reactor and OK3 materials research laboratory, including management of nuclear waste and other radioactive waste**[4]. VTT used to competitive procedure with negotiation, because the legal and technical boundary conditions for the contract (e.g., exact scope of the procurement, licensing questions related to the waste management services) were open at the time of the contract notice. The duration of the procedure was about 11 months (see Figure 34).

Figure 34. Timeline of a case example (VTT, Finland) using the competitive procedure with negotiation in contracting decommissioning and nuclear waste management services for a research reactor and radioactive materials research laboratory in 2019–20.

[4] procurement notice: https://www.hankintailmoitukset.fi/fi/public/procurement/18939/notice/43638/overview; in Finnish

Essential for the FiR 1 decommissioning project, and for fulfilling the prerequisites for the decommissioning licence, is the comprehensive contract on decom services, signed in March 2020 between VTT and Fortum. The contract covers the dismantling of FiR 1 and all necessary nuclear waste management services as well as the radioactive waste management for the decommissioning of the OK3 laboratory. An industrial partner taking responsibility of the waste management is necessary for a research organization like VTT, who does not have own nuclear waste management facilities.

Because of the complex scope, the service contract was concluded using a negotiated procedure, according to the Act on Public Procurement and Concession Contracts, as VTT is considered as a public procurement unit. In the first phase of the negotiated procedure, tenderers give preliminary (completely non-binding) tenders, based on which the procurement unit (buyer) and the tenderers undergo negotiations to specify the scope, schedule, contract terms, pricing models etc. accurately enough so that the buyer can publish a high-quality final call for tenders. In our case, the procedure was particularly useful for specifying an accurate division of responsibilities, use of VTT’s staff and the facility’s existing equipment, limiting the scope concerning the clearance of the site as well as defining nuclear liability issues and the transfer of waste management obligation between licensees.

The technical base for the dismantling work tendering was a detailed plan of the dismantling work and interim storage of the dismantling waste prepared in 2016 with Babcock Noell GmbH (BNG). BNG had previous experience in dismantling research reactors, including TRIGA-type.

The whole negotiated procedure took about 11 months and included five rounds of negotiations, individually between VTT and each of the tenderers. Prior to this formal procedure, VTT has undergone more informal discussions on industrial support for decommissioning waste management already during the operation of FiR 1, but the formal procedure and a competitive setting proved to be invaluable in reaching agreement in all matters, even the most challenging ones, within a finite timeframe.

In general, 2020 was a year of important contracts, since also the spent nuclear fuel transport and transfer contracts were concluded in fall 2020. Some of the project’s contracts have been concluded using direct procurement, because of limited availability of service providers in the market (e.g., for technical or ownership related reasons) or for security reasons. We have also used a public (open or restricted) procedure in selecting the EIA and dismantling planning consultants in 2013 and 2016.

6.3.4 Main contracts (dismantling, dismantling waste management, spent fuel management, spent fuel transport)

Combined contract on dismantling and waste management with Fortum, after careful consideration of the limited availability of services on the market, was purchased through the competitive procedure with negotiation. The negotiated procedure gave an excellent basis for detailed technical definition of requirements and consequently lower risks for both parties etc. On the other hand, direct procurements were selected in the case of limited supply, e.g., technical boundary conditions.

6.4 Lessons learned

The licensing phase of the project tested both VTT's capability to fulfil the requirements and liabilities, but also the Finnish nuclear legislation, regulations and authorities' guidelines. Exchange of experiences between VTT and authorities has led to improvements in the Nuclear Energy Act and the YVL guides issued by the Radiation and Nuclear Safety Authority STUK. Different waste streams are now better taken into account in the national waste management activities, especially via improvements in license conditions of the nuclear power plant (NPP) waste facilities. The lessons learned during the decommissioning of FiR 1 can be applied to the preparations for the decommissioning of nuclear power reactors.

Looking backward, it is easy to see that having binding contracts for waste management in place already at the moment of the shutdown decision would have simplified planning and licensing for decommissioning, saving time and expenses. In Finland, NPP operators are currently obliged to arrange their own waste management. This approach is incomplete in the sense that it might leave out minor waste streams from research institutes (like VTT), universities, hospitals, and industry. However, a task force led by Ministry of Economy and Employment in Finland (MEAE) has elaborated recommendations for further development of the national radioactive waste management [MEAE 2019], which has led to improvements for instance in the license conditions of the NPP facilities, allowing more flexible acceptance of waste streams from other operators.

Figure 35. Working methods are developed to minimize radiation exposure risk of the workers.

Open communication and transparency are important success factors in project work in general, and this applies also to nuclear projects with the exception that there are obvious limitations for full transparency due to security reasons. For VTT, the Government (represented by MEAE) is a key stakeholder, and we pay high attention to keeping MEAE well informed about the project through regular progress meetings. This dialogue concerns especially licensing requirements but also funding (see below). In parallel, effective technical communication with other stakeholders (waste acceptor, the regulator, dismantling contractor etc.) is also important to set the boundary conditions for activity characterization. If the waste endpoint is known, e.g., documentation and data management should be developed compatible with the waste acceptor organization.

In the early preparations for decommissioning, VTT had underestimated the detail required for design and planning work to meet all regulatory requirements, and consequently the time and budget of the project. Due to this, and due to the reasons detailed above, VTT faced a funding gap for decommissioning and applied in 2018 from the Government for additional funds to be paid into the Nuclear Waste Management Fund. On the other hand, the spent fuel solution in 2021 turned out to be efficient and enabled a significant reduction of future risk provisions. The *fund target* for VTT in 2022 is 8.3 million euro (i.e., the amount earmarked for remaining FiR 1 decommissioning and nuclear waste management), which already exists in the fund and is considered sufficient, all main plans and contracts being now in place. The estimated total cost for decommissioning is 23.6 million euro, out of which 15.3 million euro is already accumulated cost in 2012–2021.

6.5 FiR 1 – a pilot facility in operation and decommissioning

FiR 1 has been a key nuclear energy training and research facility for almost two generations. Now it serves as a pilot facility also in decommissioning, being a forerunner in using virtual visits in the planning, detailed activity inventory characterization, radioactive waste management between licensees, and development of free release of materials, including methods to estimate difficult-to-measure nuclides. Lessons learned can be applied to the preparations for the decommissioning of nuclear power reactors.

7 Future of Decommissioning

7.1 Decommissioning market future in Europe

The decommissioning projects of civil nuclear power plants are large projects no matter the location. The total costs of civil nuclear power plant decommissioning projects vary between few hundred million to several billions of euros depending on the plant size, plant type, quality of documentation and local regulation. Contracts of this scale are won in public tendering by some of the largest industry corporations which have sufficient experience and financial guarantees to deliver large-scale infrastructure projects. Very few Finnish companies can meet the requirements for main contracting in the decommissioning projects. Thus, acting as subcontractor within specialized niche in the supply chain includes the most likely business opportunities for Finnish companies.

Decommissioning of used nuclear power plants is a significant global market with the size of several €100B turnover over the next few decades. It is still not the only market where decommissioning expertise can be applied. The potential life-time extension plans can benefit greatly from material decay and documentation management expertise accumulated during other decommissioning activities. There are also strong signals of an emerging new wave of newbuild nuclear energy projects in Europe. Potential new development plans require understanding of site practicalities and management related to efficient decommissioning.

This report focuses on the decommissioning markets of the civil nuclear energy plants. This report is excluding the decommissioning business opportunities in the fields of research reactor, isotope production reactor and military application decommissioning activities. These decommissioning fields are more nationally coordinated and more challenging markets to enter due to the confidential nature of the operations of these facilities.

Figure 36. Various types of waste containers are deployed based on the management chain requirements.

7.2 Life-time extensions postpone decommissioning activities

The uncertainties in the European energy markets have also reflected to the forecasts of nuclear decommissioning schedules. Many countries are making quick strategy changes in national energy goals and policies by pushing the previously announced nuclear shutdown dates further while considering options for nuclear fleet lifetime extensions. This type of development will affect the nuclear decommissioning markets by postponing large decommissioning projects further in the future as described in Section 4.1 - Decommissioning Markets.

7.3 Technological and regulatory developments

The rapid development of robotic and software tools also provides new solution opportunities for the nuclear decommissioning sector. Advances in robotic component integrations, easy-to-use complex remote management software, material development and digital information models all have their useful, cost-saving and risk-reducing benefits in the nuclear decommissioning projects.

One important task in making nuclear decommissioning safer and cheaper is to also develop the nuclear energy regulation to allow the use of modern tools and standards in the industry. Obsolete regulation should not be the key reason why proven and tested innovations could not be deployed into practice. The following section describes the ongoing technological and regulatory development in the sector.

7.3.1 Forecast for robotics capabilities and costs

Extremely challenging operating environments such as Fukushima Daichi reactors 1-3 are posing new requirements for the industry. Meanwhile robotic solutions can lower the dosage rate of decommissioning workers and make general dismantling of any carrying structures safer, the melted cores in Fukushima Daichi require new decommissioning tools to be developed. One major technology developer at the accident site is Mitsubishi Research Institute which is actively seeking partnerships to innovate new solutions to be deployed.

Robotic systems are used to access and handle radioactive materials and components in contaminated areas without putting human operators at risk. These robots are equipped with cameras, sensors, and tools for cutting, welding, and handling materials. Hot cell facilities deploy these technologies daily and adding more mobility and autonomy to field operating remote handling tools can bring new cost-efficient robotic applications available for decommissioning field operations as well. Robots can conduct various valuable mapping, digital model updates, inspections, environment manipulation on transportation services according to their designed attributes.

VR and AR technologies are used for planning and simulating decommissioning activities. They provide 3D visualizations and simulations of the decommissioning process, helping operators plan and execute tasks more efficiently. Digital twins and building information models can help in design of work phases, understanding radiation risks in the process, generating material classifications and inventories and help to operate remote handling tools in the facilities. The ongoing development work focuses on creating seamless data layer integrations, user interfaces and tools to utilize the data layers in robot autonomy improvements.

Drones are employed for aerial inspections and mapping of decommissioning sites. They can provide detailed imagery and data, allowing for a better understanding of site conditions and progress. Satellite imagery, LiDAR, and GIS (Geographic Information Systems) help in monitoring and managing decommissioning sites, tracking environmental changes, and ensuring safety. Sensor information gathered from the UAVs can be further refined with analysis and simulation tools and utilized to build or update digital site models which assists the project management at making the right topical decisions.

Advanced spectroscopy and radiological measurement systems help in characterizing and quantifying radioactive waste, which is essential for proper disposal and storage. One major cost and safety concern about nuclear decommissioning relates to the transportation of radioactive materials. One way to reduce the need for radioactive sample shipping is to bring the radiological laboratories next to the decommissioning site. A concept of mobile containers with most often needed radiology laboratory equipment could significantly reduce the volume and shipping time of validation samples from the decommissioning site, reducing the project time and expensive transportation arrangements.

Advanced radiation monitoring equipment and dosimetry systems are employed to continuously monitor radiation levels and exposure to workers, ensuring their safety. This information can be updated to the digital models of the working environment to better understand the risk evolution in the changing environments. Remote dose monitoring also helps in identifying potential disturbances and risks earlier. Advanced software systems can be used for managing and tracking also radioactive waste inventories, from its generation to disposal, to ensure compliance with regulations.

AI and machine learning algorithms are used for data analysis, predictive maintenance, and decision support in decommissioning projects. They can identify patterns and anomalies in data to enhance safety and efficiency. The use of AI & ML tools requires a reliable and steady flow of data from the operations. Integrating the data collection systems with building information models and AI/ML analysis tools is essential in building successful user interfaces for complex management challenges.

Innovative materials and coatings are developed to improve the longevity and safety of storage containers, shielding, and protective equipment. Radioactive resistant electronics is also an important field of research, since that can assist various remote handling tools to last longer in challenging environments and conduct missions in extremely challenging environments, such as advanced nuclear reactor cores, novel fuel laboratories, spent nuclear fuel management systems and nuclear accident sites.

7.3.2 Regulation to enable technology utilization

Technology alone will not make nuclear decommissioning more efficient or safe. The regulation environment can also significantly contribute to the deployment of innovation and increased productivity in the decommissioning sites. Strict nuclear safety regulations are often made to ensure the safety and security of decommissioning activities, but they may also act as the main bottle neck in deploying the latest methods and tools in practice. The nuclear regulation environment is among the least internationally harmonized fields of legal operation environments which may cause significant challenges in scaling up methods and solutions between different countries. To ensure that the regulation environment may enable development in the field of nuclear decommissioning the following aspects should be considered.

Regulators can establish technology-neutral guidelines that focus on desired outcomes and safety standards rather than specific methods or technologies. This allows flexibility for the use of emerging and innovative solutions Regulations can incorporate risk-informed decision-making principles, which consider the specific risks and benefits associated with new technologies. This approach allows for more tailored and efficient regulatory requirements. Transitioning from prescriptive to performance-based regulations can enable the use of novel technologies. Operators would need to demonstrate that their chosen technology meets safety and performance criteria rather than following a strict set of rules.

Regulatory agencies can establish regulatory sandboxes or pilot programs to test and evaluate new technologies in controlled environments. This allows for learning and adaptation before full-scale deployment. Regulators can collaborate with industry experts and technology developers to better understand and assess the safety and feasibility of new technologies. This partnership can lead to informed regulatory updates. Implementing expedited approval processes for new technologies in decommissioning can reduce bureaucratic delays and encourage innovation. Regulatory agencies may develop streamlined pathways for assessing and approving novel solutions. Regulations can provide flexibility in documentation and reporting requirements, recognizing that innovative technologies may not fit traditional reporting formats. This can reduce administrative burden and promote the use of novel solutions. Regulatory agencies can commit to periodic reviews of existing rules to ensure they remain relevant in the face of technological advancements. This process can lead to timely updates that accommodate new technologies.

Encouraging international harmonization of regulations can facilitate the acceptance of novel technologies across borders. Consistency in regulatory requirements makes it easier for technology developers to bring their solutions to multiple markets. Regulators can work with industry stakeholders to establish training and certification programs for the safe operation of new technologies. Ensuring that personnel are adequately trained can be an important aspect of regulatory compliance. As new technologies often involve digital systems and connectivity, regulations should address cybersecurity measures to protect against cyber threats and potential vulnerabilities.

7.4 Future of Finnish Decommissioning Ecosystem

Lifetime extension plans for the current Finnish nuclear generator fleet will postpone the decommissioning operations in Finland. Loviisa plants have already received a license for lifetime extensions and Olkiluoto plants 1 & 2 are also entering the extension process. It is highly likely that after FiR1 is successfully dismantled there will be no nuclear energy decommissioning sites in Finland for a few decades. On the other hand, there are facilities using radiation sources which will require expertise in active material handling and low-level waste management. Overall keeping up the good management practices in the operating nuclear generators will ensure lower decommissioning costs in the future while management practices and decommissioning plan update methods may be improved meanwhile. Knowhow in decommissioning is still valuable information for planning the potential new reactors to be easily dismantled and managed. Also, lifetime extension plans benefit from long-term lifetime management experiences which shows what parts wear, tear and activate during long-term operation.

The Finnish decommissioning ecosystem will evolve to target the export markets. With good experience and reputation Finnish stakeholders are in a good position to tap into the ongoing and upcoming decommissioning activities within EU and beyond. As rather small organizations with limited capital and ability to carry liability risks it is advisable for the Finnish decommissioning suppliers to find themselves as subcontractors in the European decommissioning projects or as solution developers in the industry. Finnish Decommissioning Ecosystem should continue the dialogue about organizational strengths, development focus and opportunities for co-tendering service packages to the decommissioning site managers.

7.4.1 Small and Advanced Modular Reactor waste management

Next topical question for the Finnish nuclear energy decommissioning ecosystem is the potential new SMR & AMR projects and their lifetime management services.

Potential expansion of the current European nuclear generator fleet with different sizes – from large conventional plants to Small Modular Reactors (SMR) - of light water reactors may increase the amount of generated spent fuel and decommissioned material. This development would require expansion of planned radioactive waste management facilities or siting and planning of new facility locations. This development would also benefit from the decommissioning industry's experience on nuclear site planning and retrofitting, and the lifetime extension and decommissioning design of the new reactor sites. It is highly advisable to spend effort on planning an efficient decommissioning process when making lifecycle simulations of the new reactor plants.

Introduction of Advanced Modular Reactors (AMR) with novel fuel assemblies and cooling mediums will require validation of a range of new safety cases for decommissioning and waste management practices. The new technologies that produce long-lasting radioactive waste materials require research efforts to ensure that the generated waste can be sustainably managed in the end of its lifecycle. Making geological repository method validation is a long and expensive process that will require many years of practical testing, laboratory research and result analysis. It is important to make informed strategic decisions about the technology choices in good time, since the development pathways are long and costly but also provide opportunities for great competitive advantages if the technology choices are right and if the research efforts generate implementable results.

Monitoring the development of nuclear and other energy and medical industry roadmaps is essential to gain complete understanding about the development of nuclear decommissioning business opportunities globally.

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Author(s)	Olli Soppela, Markus Airila, Tatu Harviainen, Ilkka Karanta, Marja Liinasuo, Anna-Elina Pasi & Tapani Ryynänen
Abstract	Decommissioning of nuclear power plants (NPP) presents a significant business opportunity with high market potential, particularly in Europe. Projects are large-scale and costly, requiring companies to have specialized knowledge in the nuclear industry but also conventional demolition expertise. This final report summarizes the achievements of the dECOmm project, which VTT launched to establish a Finnish ecosystem capable of providing competitive services to the international decommissioning market. The project started at the end of 2019 and concluded in June 2023. The dECOmm project was one of the first co-innovation projects funded by Business Finland, The project has proven the efficacy of an ecosystem approach in fostering innovation, societal impact, and both domestic and international networking. Dissemination of project results and demos took place in Open Business Day events, DigiDECOM conferences in Norway and Finland, several other international conferences, field trips and the final seminar. Networking and dissemination activities were integrated with nuclear energy ecosystems EcoSMR, ECO-Fusion and FINUELS. Project members were VTT (research partner), BMH Technology, Ekonia, Fortum, Lotus Demolition, Platom, Sweco and TVO. Additionally, FinNuclear Association was a close collaboration partner.
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Nimeke	**Ecosystem for New International Decommissioning Services** dECOmm-projektin (2019-23) loppuraportti
Tekijä(t)	Olli Soppela, Markus Airila, Tatu Harviainen, Ilkka Karanta, Marja Liinasuo, Anna-Elina Pasi & Tapani Ryynänen
Tiivistelmä	Ydinvoimalaitosten käytöstä poistaminen tarjoaa merkittävän liiketoimintamahdollisuuden, jolla on suuri markkinapotentiaali erityisesti Euroopassa. Projektit ovat mittavia ja kalliita, ja ne edellyttävät ydinalan yritysten erikoisosaamista, mutta myös tavanomaista purkuosaamista. Tämä loppuraportti tiivistää VTT:n käynnistämän dECOmm-hankkeen saavutukset. Hanke alkoi vuoden 2019 lopussa luomaan suomalaisen ekosysteemin, joka pystyy tarjoamaan kilpailukykyisiä palveluita kansainvälisille käytöstäpoistomarkkinoille, ja päättyi kesäkuussa 2023. dECOmm-hanke oli yksi ensimmäisistä Business Finlandin rahoittamista co-innovation-projekteista. Hanke on osoittanut ekosysteemi-lähestymistavan tehokkuuden innovaatioiden ja yhteiskunnallisia vaikutusten edistämisessä. Merkittävä osa hankkeen vaikutuksista syntyy tehokkaasta kotimaisesta ja kansainvälisestä verkostoitumisesta. Hankkeen tuloksista ja demoista viestittiin erityisesti Open Business Day -tapahtumissa, DigiDECOM-konferensseissa Norjassa ja Suomessa, useissa muissa kansainvälisissä konferensseissa, kenttämatkoilla ja loppuseminaarissa. Verkottumisessa ja tulosten levittämisessä muut ydinenergia-alan ekosysteemit (EcoSMR, ECO-Fusion ja FINUELS) olivat tiiviisti mukana. Hankkeessa olivat mukana VTT (tutkimuskumppani), BMH Technology, Ekonia, Fortum, Lotus Demolition, Platom, Sweco ja TVO. Lisäksi FinNuclear ry toimi läheisenä yhteistyökumppanina.
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Ecosystem for New International Decommissioning Services

Final report - dECOmm project 2019-23

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