VTT Technical Research Centre of Finland

Case Study on Decommissioning of the FiR 1 TRIGA reactor

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Summary

This report summarizes the experiences and lessons learned VTT Technical Research Centre of Finland has accumulated to date from the transition of the Finnish research reactor FiR 1 from operation into decommissioning. The report focuses to the period of about 10 years starting from re-licensing in 2011, followed by shutdown decision, Environmental Impact Assessment for decommissioning, planning licensing and contracting of decommissioning, necessary organizational changes and competence management, and completed decommissioning actions to date. We

(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.

The case study is motivated by the International Atomic Agency IAEA's request to VTT to prepare such a case study. The aim is to contribute to IAEA's initiative on providing guidance on the consideration of decommissioning aspects to the designers and operators of research reactors. IAEA has under elaboration a Technical Report Series (TRS) publication on *Considerations on Decommissioning in the Design and Operation of Research Reactors* (tentative title). IAEA may use the content as such or in an edited format as an Appendix of the TRS publication.

Parts of the content have been previously published by the authors in [Airila 2015, 2020, 2021a, 2021b, Auterinen & Kivelä 2011].

Confidentiality	VTT Public

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Preface

Experience has shown that it is essential to start with preparations for decommissioning at a very early stage, at best during the design stage of the facility, and at least during the operational stage. Planning is a key issue to minimize delays and undue costs; to optimise personnel and other resources; and to initiate preparatory activities for decommissioning in a planned, timely and cost-effective manner, with the overall objective of ensuring safe and efficient decommissioning.

This report summarizes the experiences and lessons learned that VTT Technical Research Centre of Finland has accumulated to date from the transition of the Finnish research reactor FiR 1 from operation into decommissioning. The report focuses to the period of about 10 years starting from re-licensing in 2011, followed by shutdown decision, Environmental Impact Assessment for decommissioning, planning licensing and contracting of decommissioning, necessary organizational changes and competence management, and completed decommissioning actions to date.

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The work reported herein is a team effort, which we have only written up on behalf of our present and former VTT colleagues, so there's a good reason to write a long paragraph of acknowledgements. Contributors in the decommissioning phase include Eric Dorval, Aku Itälä, Joonas Järvinen, Emmi Myllykylä, Esko Ruokola, Merja Tanhua-Tyrkkö, Olli Vilkamo, Merja Airola, Kim Calonius, Asta Forsell, Juha Forsström, Tuukka Hahl, Jouni Hokkinen, Silja Häkkinen, Mikko Ilvonen, Anne Kemppainen, Emma Kleemola, Virpi Kupiainen, Topias Käyhkö, Maarit Lahti, Tiina Lavonen, Jari Likonen, Nora Pyhälammi, Tuuli Raatikainen, Jukka Rossi, Erja Schlesier, Jarmo Siivinen, Vesa Suolanen, Susanna Teppola, Kaupo Viitanen, Pekka Viitanen, Christina Vähävaara, Marja Ylönen, and many others including all our supervisors at VTT. Our long partnership with Anni Jaarinen, Matti Kaisanlahti, Antti Ketolainen, Petra Lundström, Ville Oinonen, Jukka Rahnasto and their colleagues at Fortum, as well as with Tapio Lahtinen and Uttrang Thor-Touch from PTC Services during 2019–20 greatly advanced the licensing, vital for VTT's project. While the Finnish authorities MEAE and STUK are demanding, we at VTT want to acknowledge their solution-oriented attitude and willingness to exchange constructive feedback. Moreover, we at VTT are grateful for the various ways of support that our project has received from other domestic and international stakeholders.

Espoo, Finland, 31.1.2022

Authors

Contents

1. Introduction

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 1). The reactor is now defueled and in a permanent shutdown state, the technical maintenance and security surveillance of the reactor and the premises continuing. Preparations for decommissioning are close to completion. 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 1. 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 a sufficient number of 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.

In this Section, we summarize the uses of FiR 1 over the reactor lifespan, reasons for and implications of the decision to shut the unit, ageing management after the shutdown decision, and the arrangement for spent fuel management.

1.1 Early history

The reactor was purchased through an agreement between the International Atomic Energy Agency (IAEA) and the government of Finland for assistance by the agency to Finland in establishing a research reactor project. The purchasing contract between General Atomics and the Government of Finland was signed May 30th 1960. The fuel for the reactor was purchased through four Supply Agreements between the IAEA, the Government of Finland and the Government of the United States of America. The first agreement entered into force on 30 December 1960 and the fourth on 27 November 1969. The last fuel delivery arrived at the reactor January 4th 1971. All fuel is 19,9% enriched uranium. The FiR 1 reactor project at the IAEA was the first one concluded in this trilateral form and formed the prototype for next research reactor projects. [Auterinen 2015]

FiR 1 was started ceremonially in the Otaniemi campus in Espoo on 31 August 1962 (the first criticality was achieved earlier on 27 March 1962). The opening culminated in a power pulse launched by Urho Kekkonen, the long-standing president of Finland. The 1960's was a decade of training and basic research in reactor physics and formed the basis for all upcoming operations. The facility acted as a central place of training for the key persons of the two Finnish nuclear power companies IVO (later Fortum) and TVO that started their power generating units Loviisa 1–2 and Olkiluoto 1–2, respectively, during years 1977–1980.

The most remarkable project in the early years was the power upgrade from 100 kW to 250 kW in 1967. The motivation for the project was not to increase the thermal power but specifically the neutron flux in order to carry out all irradiations in a shorter time, and a flux level of 10^{13} n/cm^{2}s was achieved. At the beginning of the power upgrade project the whole power range up to 1 MW was considered, but model calculations, supported by indirect measurements, showed that the durability of aluminium-cladded fuel elements poses a significantly lower limit for safe operation. Power levels up to 318 kW were tested in February 1966 and a new nominal power of 250 kW was confirmed safe [Hiismäki 1999].

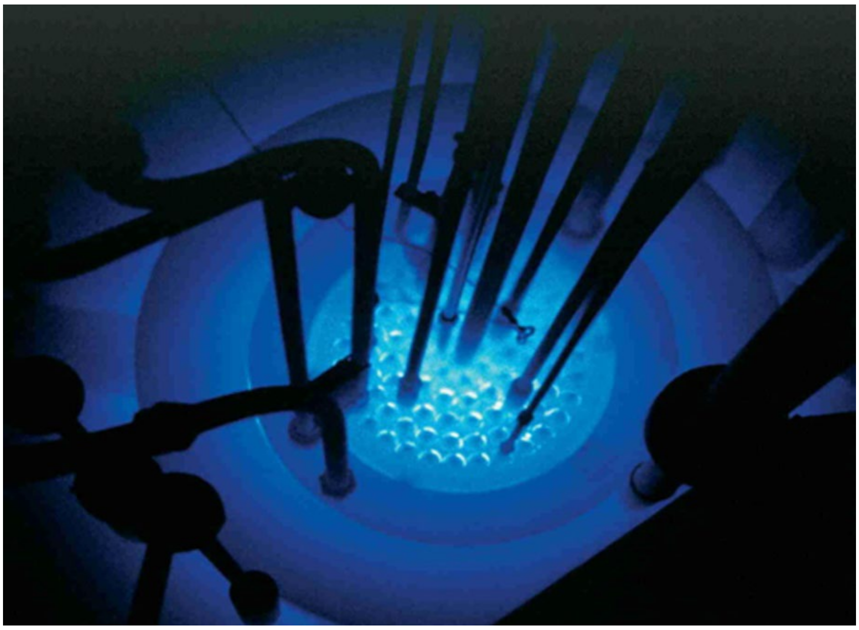

Figure 2. The core of FiR 1 in operation.

In the 1970's neutron activation analysis was developed intensively by installing sample changers and automatic gamma spectrometers with analysis software for instrumental multi-element analysis [Lipponen & Rosenberg 1988]. For uranium ore prospecting a rapid pneumatic transfer irradiation system with delayed neutron counting was developed [Rosenberg et al. 1977]. The activity evolved into a cost-effective service for companies carrying out ore exploration in Finland and Sweden, and in particular for the broad geochemical survey carried out by GTK (Geological Survey of Finland). The number of samples analysed annually approached 50,000 and the developed technology was also exported to some other countries. The analysis of some lunar samples from Apollo 12 were trusted to FiR 1 [Rosenberg 1971].

In the 1970's the first version of a reverse time-of-flight diffractometer (ACTACUS) was developed and in the 1980's in collaboration with the nuclear physics institute of Leningrad a novel system based on a Fourier chopper and dedicated electronics was constructed. One of these devices is still in use at JINR in Dubna, Russia (HRFD). [Balagurov et al. 2015]

In 1981, to enable reliable operation for another 10 to 20 years, a renewal of the reactor control instrumentation was carried out in cooperation with the Central Research Institute for Physics (KFKI) at the Hungarian Academy of Sciences, which delivered the nuclear part of the instrumentation and with the Finnish company Valmet Oy instrument works, which delivered the conventional instrumentation, including the automatic power control system and the control console. [Bärs & Kåll 1982]

1.2 Development of BNCT at FiR 1

A major upgrade took place in the 1990's when the reactor was complemented with radiotherapy equipment [Auterinen et al. 2001, Auterinen & Salmenhaara 2008a,b]. The goal was to achieve an intensive and clean epithermal neutron beam for Boron Neutron Capture Therapy (BNCT). Due to the low power level of the reactor, the treatment aperture had to be positioned as close to the core as possible to obtain sufficient beam intensity for practical treatments. This was realized by removing the thermal column and part of the concrete shielding of the reactor to release space for the treatment station, see Figure 3. The loading of the core was modified to maximize the flux towards the aperture. The vicinity of the aperture to the core required the development of an optimal moderator material that could sufficiently reduce the dose from direct gamma radiation and fast neutrons. Materials screening led to the observation that aluminium and fluorine would form an effective epithermal moderator. The development yielded the FLUENTAL™ moderator consisting of 69% aluminium fluoride, 30% metallic aluminium and 1% lithium fluoride for absorbing thermal neutrons. The constituents were combined into a metal-ceramic product (density 3 g/cm^3) by hot isostatic pressing. VTT has delivered this patented BNCT material to the UK, Taiwan and three BNCT projects in the US.

Clinical trials showed especially with head and neck tumours improved tumour control and survival of the patients [Kankaanranta et al. 2012]. BNCT treatments at FiR 1 conducted in collaboration with Boneca Ltd and Helsinki University Central Hospital were included in the national healthcare service system. Unfortunately this radiotherapy service ended in the bankruptcy of the Boneca Ltd, which organised the treatments, in January 2012. Totally over 300 patient irradiations were given at FiR 1.

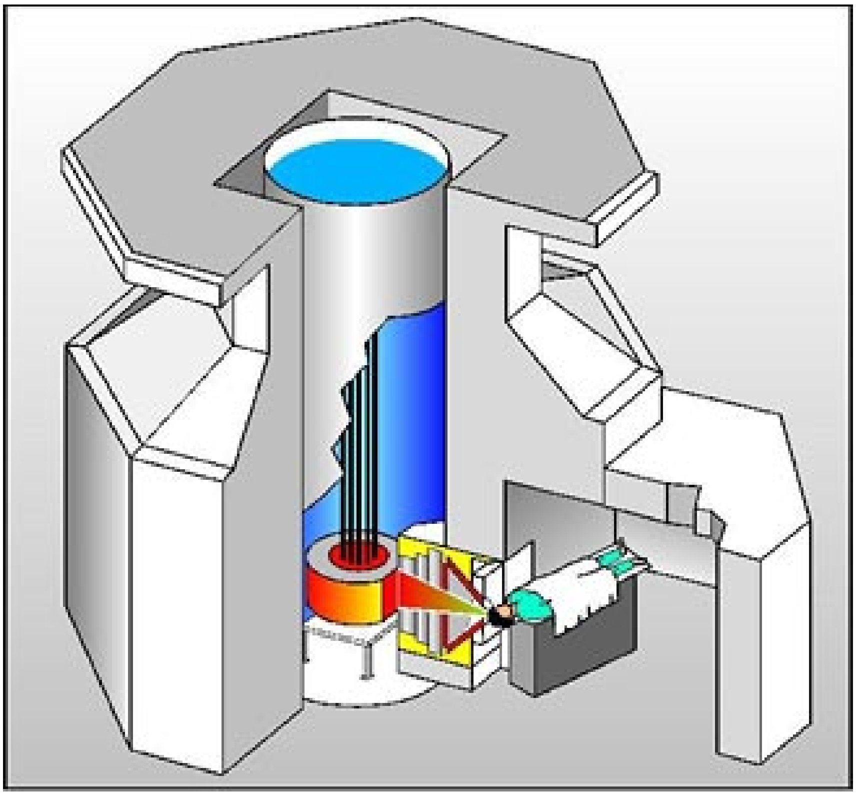

Figure 3. Schematic of FiR 1 with the BNCT treatment facility.

Due to the BNCT project, FiR 1 became an important research and education unit for medical physics. Since the early 1990's several graduate and postgraduate students from the medical physics program of the University of Helsinki worked at the facility and were credited up to one year of required hands-on experience for the hospital physicist exam. Research projects included dosimetry, radiation transport modelling, treatment planning, prompt-gamma imaging and other medical physics aspects of BNCT.

1.3 Isotope production for industry and medicine, education, and other service activities during the last years of operation

The main use of the reactor after end of the BNCT treatments in 2012 was radioisotope (^{82}Br, ^{24}Na and ^{140}La) production for tracer studies in industry. The applications of the isotopes are calibrations of liquid or gas flow meters and analysis of disturbances in chemical or other processes. The total yearly production was between 3 and 4 TBq. Earlier also ^{153}Sm was produced for bone cancer treatment and ^{165}Dy for treatment of arthritis. The spin-off company established at the reactor in 1999, MAP Medical Technologies, has been successful but relies now on other sources for its radioisotopes, the accelerator at the Jyväskylä University in central Finland and international radioisotope producers.

Neutrons from FiR 1 were also used for testing of scientific equipment. Neutron-tolerant MEMS (Micro Electro Mechanical System) magnetometers for the ITER fusion reactor and new radiation detection and imaging devices were tested by irradiating them in the reactor.

Activation analysis was used for only some exotic applications like nuclear power plant accident studies and nanoparticles for radiotherapy development.

Aalto University had yearly two courses for technical physics and energy technology students in reactor and neutron physics that utilized the reactor. One-day intensive courses with hands-on exercises, or demonstrations and excursions in connection to longer lecture courses, were organised also for students of Lappeenranta University for Technology and the personnel of nuclear power companies. In particular, the number of Swedish nuclear professionals trained at FiR 1 in 2007–2014 is over 300. Now this kind of training is organised in other European sites, e.g. in Czech Republic.

The capacity factor of FiR 1 over the whole lifespan is shown in Figure 4. During the last years the total operating costs of FiR 1 were in the range of half a million € annually, including all personnel costs of the whole reactor organization as well as cost of premises.

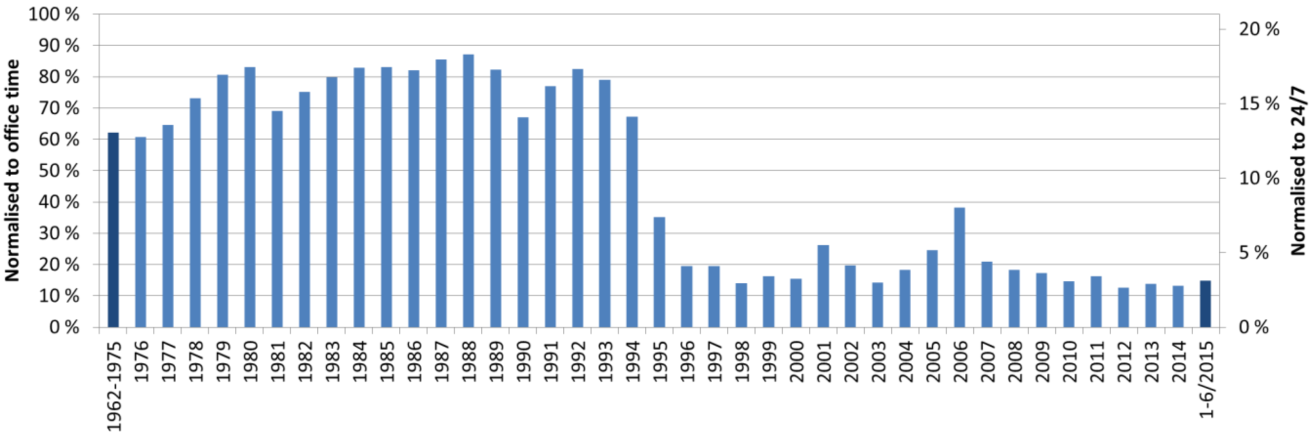

Figure 4. Capacity factor [Left axis: annual thermal output / (nominal power x 1840 h); Right axis: annual thermal output / (nominal power x 8760 h)] of FiR 1 during 1962-2015. The reactor was operated practically full office time until 1994. BNCT operations in 1999-2012 involved only short uptime of 20-60 min per patient, which shows as a significantly lower capacity factor.

1.4 Ageing management

Nuclear energy legislation in Finland requires that also a research reactor shall have a document describing ageing management. At FiR 1, the IAEA draft safety guide DS412 *Ageing Management for Research Reactors* was used in creating the ageing management system at FiR 1 prior to the license renewal in 2011. The work included extension and improvement of inspection and service procedures, creation of an obsolescence management system for the systems, structures, and components (SSC´s) and identification of the SSC´s important to safety and reliable operation of the reactor as well as their degradation processes that affect safety and reliability [Auterinen & Kivelä 2011].

The ageing management system includes procedures for detection and assessment of ageing effects as well as for prevention and mitigation of ageing effects. To improve the ageing management the quarterly and yearly inspections were extended to all SSC´s and the data logging was improved to aid the analysis of the ageing process. The inspection of the reactor tank walls and beam tubes includes a wider selection of methods and the number of inspection points was increased.

The introduction of the ageing management program for FiR 1 almost coincidences in time with the decision to shut down the reactor, but the two events were not related. In fact, at the end of 2011, VTT was granted a new operating license that would have been valid until the end of 2023. The shutdown decision came soon after in July 2012, since the company responsible for BNCT treatments was declared bankrupt. Despite the sudden change of plans, VTT has continued implementing the ageing management program also in the permanent shutdown state to maintain a good condition of all SSC’s.

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

The amount of irradiated fuel at FiR 1 after operation from 1962 to 2015 was 103 elements (about 15 kg U of which 3 kg ^{235}U). The fuel was subject to the return programme of US DOE, which was set to expire in May 2019 but was extended to May 2029 just before its expiry. The primary scenario for disposal of the nuclear fuel was to send it to Idaho National Laboratory (INL) in the USA where similar batches of nuclear fuel from TRIGA research reactors have previously been returned from various countries. The programme has, however, been halted from 2014 as Idaho State is blocking all nuclear waste transports to INL due breaches of Idaho Settlement Agreement. Since fuel removal from the site is such a key step in decommissioning, this blockage was a long-standing challenge for VTT in planning, licensing and contracting the following phases.

VTT considered US return as the primary option for spent fuel and constantly maintained the possibility since 1981. Even the timing of the permanent shutdown of FiR 1 was decided such that it fulfilled the fuel return programme requirements (i.e., before May 2016). In parallel, VTT maintained a secondary option – final disposal in Finland, which would however have required proper additional licensing of the encapsulation and spent fuel disposal facilities that are now under construction by Posiva in Olkiluoto, Western coast of Finland.

In July 2020, the U.S. Geological Survey (USGS) in Denver, Colorado, informed VTT that USGS would need additional fuel to continue operating its reactor. As the production of suitable fuel had been suspended for several years and was not available on the market, it was of mutual benefit for both parties that used FiR 1 fuel would be transferred to the USGS for further use in its reactor. The fuel has a remarkable remaining utility value, the maximum burnup being about 24%. At the end of operation, the United States Department of Energy will take care of the fuel.

The contract for the supply of used fuel was concluded in November 2020, and VTT arranged for the safe international transport of the fuel from Espoo, Finland to the USGS with support from Edlow International Company. The transport of fuel by road and sea was supervised by the Finnish Radiation and Nuclear Safety Authority (STUK) and USA regulatory and safety authorities. In January 2021, the USGS received all the irradiated fuel from FiR 1.

Arranging for cooperative international spent fuel management abroad is an exception permitted by the Nuclear Energy Act. Before sending the fuel abroad, Finland received a report from the USA authorities on their commitment to the management of the fuel batch. It is planned that when the USGS ceases to use its reactor, all its irradiated fuel will be delivered to INL.

2. Description of the FiR 1 reactor

2.1 Technical characteristics

The supplier, General Atomics, has designed the TRIGA reactors for use in university environments. The name TRIGA comes from Training Research Isotopes General Atomics. Also FiR 1 was originally in the possession of Helsinki University of Technology (which became the Aalto University in 2010), but it was transferred to VTT Technical Research Centre of Finland by government decision in 1971. In this Section, we summarize the reactor design with its unique characteristics and the extensive characterization that has been done in order to collect reliable background data for the planning of dismantling, nuclear waste management and all related project activities. The main nuclear characteristics of the FiR 1 reactor are listed in Table 1.

Table 1. Main nuclear characteristics of the FiR 1 reactor.

Type	TRIGA Mk II (open tank reactor with graphite reflector)
Maximum steady-state thermal power	250 kW
Maximum pulse power (duration 30 ms)	250 MW
Maximum excess reactivity	4 $
Maximum thermal neutron flux	1.0 × 10^{13} n/cm^{2}s
Fuel composition	Uranium-zirconium hydride (about 8 % U, 91 % Zr, 1 % H in weight)
Uranium enrichment	19,9 %
Core loading	2.7 kg ^{235}U (13.7 kg U)
Fuel element cladding	0.76 mm aluminium or 0.5 mm stainless steel
Dimensions of the active configuration	355 mm × 436 mm (height × diameter)
Control rods	Three boron carbide rods, one boron graphite rod (pulse rod)

2.2 Estimate of radioactive materials and waste generation

2.2.1 Overview of waste characterization strategy

We present here in more detail our approach to activity characterization, since it provides the basis for waste management planning and cost estimation and has been the most valuable single set of input data for several purposes. Updating the activity inventories regularly during reactor operation is especially important with research reactors, since their operating history typically contains different applications and modifications to the reactor structures. Data on e.g. operating hours in each configuration and activating impurities in the reactor structures can easily be lost, if future decommissioning is not taken into account early enough. Figure 5 illustrates the progress of characterization process throughout a decommissioning project phases.

VTT's waste management is based on nuclide vectors and the scaling matrix approach. Material-wise nuclide vectors will be applied during the dismantling as presented in Figure 6. Characterization work in 2015–2020 has focused on validating the calculated results by collecting samples from different materials. An important limiting factor has been that since the spent fuel was still in the reactor core in 2015–2020, samples could be drilled only from the low active outer areas of the reactor, to avoid damaging the tank or core structures (Figure 7).

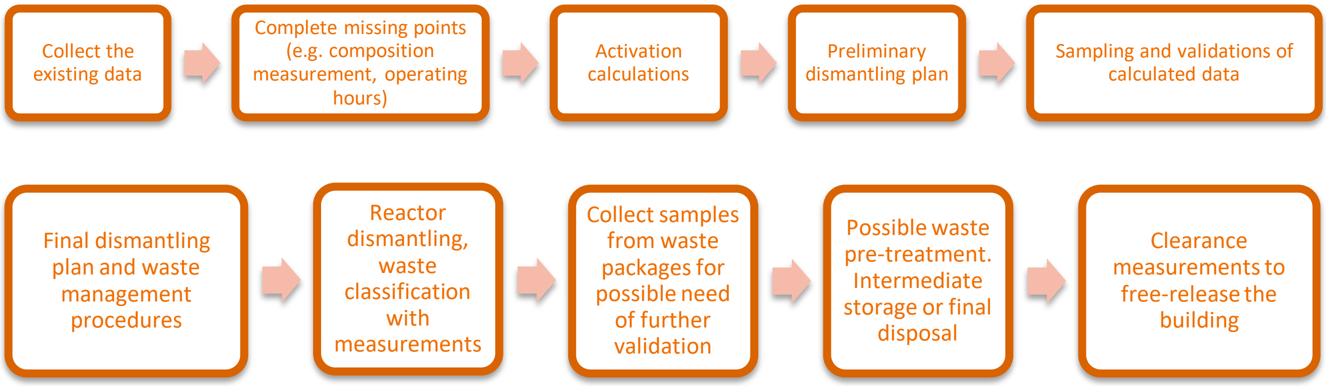

Figure 5: Progress of characterization throughout the project phases.

2.2.2 Activity calculations and formation of nuclide vectors

In the preliminary phase, VTT conducted activity calculations using a model that combined several MCNP neutron flux models representing different reactor operation phases to ORIGEN-S point-kinetic calculations to take into account the operation hours in each configuration. Since this model assumes that the target is mathematically homogeneous, the ORIGEN-S calculations were repeated for all the reactor main components and structures separately [Kotiluoto & Räty 2015, Räty & Kotiluoto 2016, Räty 2020]. These results were used in the preliminary waste estimates and dismantling plan.

VTT-Fortum contract in 2020 (see Section 3.4) has enabled setting Loviisa NPP waste acceptance criteria as boundary conditions to waste management planning. Therefore, forming the validated nuclide vector has been set to follow ISO 21238:2007 standard [ISO 2007] and special challenges related to especially waste final disposal can be discussed directly with the final repository facility owner.

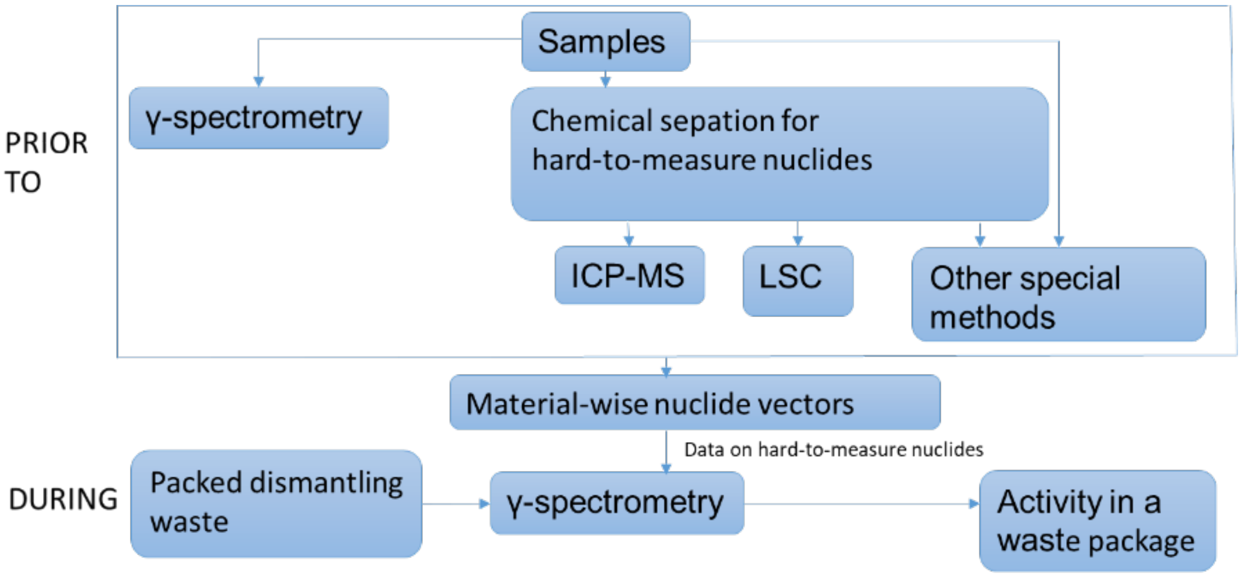

Figure 6: Waste classification using nuclide vectors. Here ICP-MS = Inductively Coupled Plasma Mass Spectrometry and LSC = Liquid Scintillation Counting.

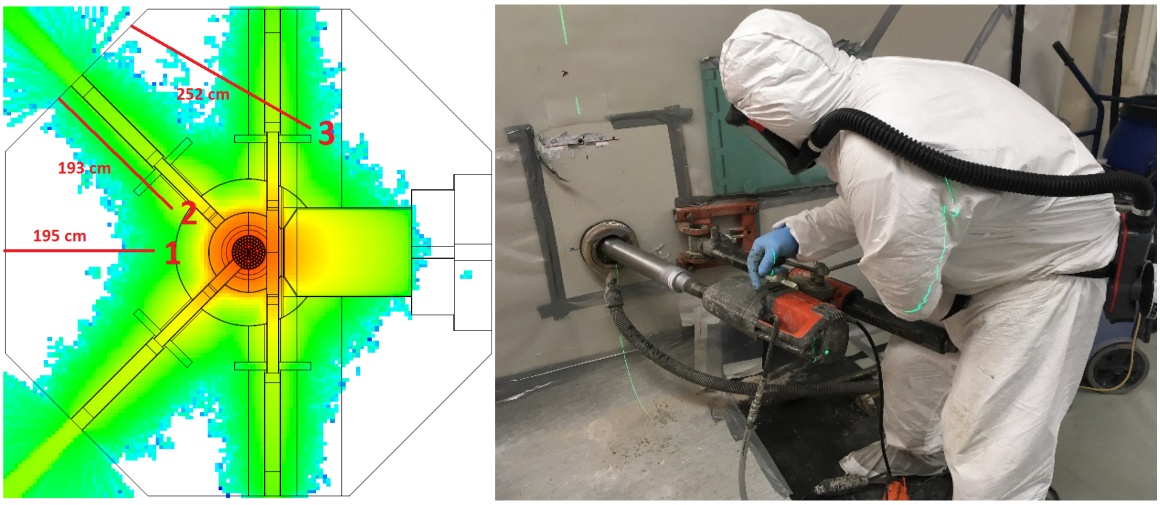

Figure 7: Left: Drilling directions towards the activated parts of the FiR 1 biological shield concrete (red lines 1, 2 and 3), drawn on top of MCNP geometry and MCNP calculated neutron flux distribution map. Right: Drilling the specimens from the biological shield.

Choosing the final waste management option and forming the nuclide vector always contain some assumptions between scientific precision and practical feasibility. Practical questions have been e.g.

- Activity in structures is so low that the amount of difficult-to-measure (DTM, or hard-to-measure) nuclides in the vector cannot by validated by sampling. In these cases DTM measurements are not feasible. The characterization is performed by measuring the material composition from samples, performing the activity calculations using the measured composition and finally forming the nuclide vector by gamma spectrometric measurements using scaling factors.

- The FiR 1 reactor contains several different types of steel, but the quantities are so low that it is not feasible to try to form nuclide vectors separately for each one. The best approach has been to form only one vector using conservative assumptions and checking with the waste acceptor that the list contains all the relevant nuclides.

- Relevant key nuclides have been identified as ^{60}Co, ^{137}Cs and ^{152}Eu. In addition, the FiR 1 epithermal neutron beam facility for cancer patient treatments using the boron neutron capture therapy (BNCT) contains Fluental^{TM} neutron moderator and lithium containing plastics, activated practically only through activation reaction ^{6}Li (n,α) ^{3}H. In the lack of gamma activity, they don't have a suitable key nuclide and have to be characterized using only sample measurements and averaging the results to larger waste masses. Calculations are still utilized to choose suitable sampling locations, maintaining conservatism. Some structures contain also hazardous waste (lead, cadmium etc.) not allowed in Loviisa final disposal repository. Fortunately, these contain mainly short-lived nuclides, so they can be eventually free-released via aging in interim storage.

- How to measure the nuclides as a result of contamination from reactor operation (isotope production and activation analysis)? Current approach is to measure only gamma active nuclides and supplement the data with historical records of reactor operation.

- Since some of the material are inaccessible before dismantling commences, the approach has been that VTT will form preliminary calculated nuclide vectors with conservative assumptions and these will be further refined and validated by Fortum during dismantling.

It has been estimated that altogether VTT will need 15 nuclide vectors. It is a relatively large number, but illustrates the special challenges in research reactor with various material and structural modifications throughout the facility operating history.

2.2.3 Experimental characterization and development of methods

Radiochemical method developments for DTM radionuclides have been a collaborative effort between modelling and experimental studies. The modelling results have provided material wise lists of DTMs with conservative activity concentration. This information has been the basis for radiochemical method developments as both DTM's and interfering gamma emitters could be accounted for i.e. the effort could be efficiently targeted on the most relevant radionuclides. DTM radionuclide analyses are long processes as the radionuclides first need to be quantitatively extracted from solid matrix. For example, solubility of concrete [Leskinen et al. 2021a] and graphite [Räty et al. 2019] are a major challenge in their analysis. Secondly, the DTM of interest requires complete separation from interfering radionuclides. For example, complete purification of ^{63}Ni from ^{60}Co is required for accurate analysis [Leskinen et al. 2020a]. The DTM analyses can also suffer from radionuclide volatility, quenching in liquid scintillation counting etc. Therefore, method validation is required and in many cases it can be carried out using reference materials. However, there are no commercially available reference materials for DTM analyses in decommissioning waste and therefore validation via intercomparison exercises has been carried out for steel [Leskinen et al. 2020b] and concrete [Leskinen et al. 2021b] organized in Nordic nuclear safety research community. In total 8 laboratories have participated, 3 from Finland, 1 from Sweden, 1 from Denmark, 2 from Norway and 1 from France. Current intercomparison exercise focuses on DTM analysis in spent ion exchange resin. The exercises have highlighted the importance of collaboration and information exchange between laboratories.

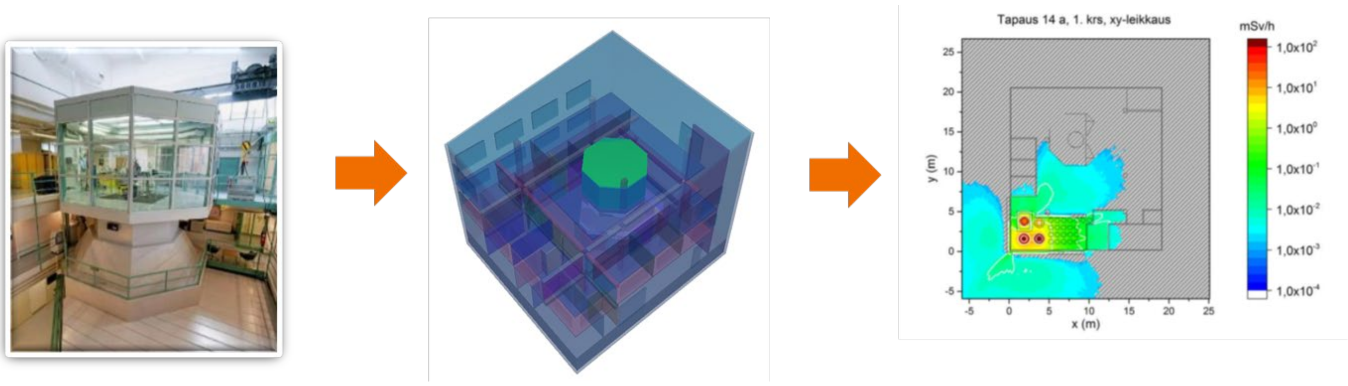

Figure 8: Direct radiation doses to the public have estimating using an MCNP model of the building. Some of dismantled heavy structures of the reactor will be utilized as extra shielding close to the building outer walls.

2.2.4 Applications of inventory data in planning

Along with validating the nuclide vectors, characterization work in 2015–2020 has also included applying the results in especially radiation safety planning and waste final disposal safety assessment. VTT-Fortum agreement has also been essential to set the boundary conditions for this planning. Practical questions include e.g.

- Intermediate waste storage in the research reactor facility area (a couple of months at a maximum) is a challenge, since the reactor is located in a university campus area and all radiation dose to public must be prevented. Building an MCNP virtual model of the reactor building has enabled estimating direct doses through the building walls. [Haapamäki 2018] The current plan is to use dismantled free-released heavy structures from the reactor to provide extra shielding. This is illustrated in Figure 8.

- Choosing the waste packages is compromise between several factors. E.g. the packages have to provide enough shielding, but reactor hall crane and doorways set limitations to package size and weight. Logistics and requirements in both public road transportation and final repository site also need to be taken into account. This is illustrated in Figure 9.

- Special material and certain long-lived nuclides have to be taken into account in the safety assessment of final disposal (which barriers are needed, do the packages have to provide a barrier in waste final disposal).
- Validating all the methods used in waste classification and sufficient environmental safety procedures.

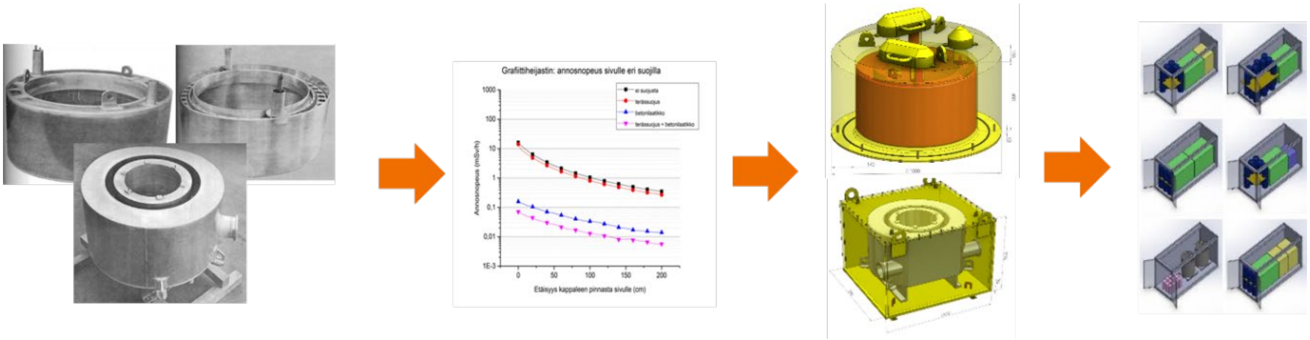

Figure 9: Package planning has included studying options taking into account sufficient shielding, logistics and safety of final disposal; illustrated here for the radial graphite reflector of the core [Tommila & Seitomaa 2021].

3. Organization & Management during the transition period – between shutdown and decommissioning

3.1 Safety culture in transition to decommissioning

From a technical point-of-view, the risk landscape changes remarkably when a nuclear facility ceases operation and enters the decommissioning phase. The main safety goals during operation (controlling the nuclear chain reaction, ensuring cooling of the fuel, and confining the radioactive fission products) become irrelevant at the latest when the irradiated nuclear fuel is removed from the facility. While general radiation protection requirements (shielding from direct radiation and contamination control) become very prominent during specific (early) decommissioning tasks, they can eventually be gradually relaxed along with the progress in decommissioning. In addition, the decommissioning phase brings significant new industrial risks related to the demolition, involving various issues such as cutting work, heavy lifts and transports, work on scaffolding and from cranes, dust, noise etc., all of which require the operator and their contractors to adopt completely new safety practices on-site.

From the organisational and attitudinal point-of-view, during decommissioning the workplace changes from a steady-state facility into an ever-changing environment. This challenges the mind set of all employees, which is also highlighted by [IAEA 2018]: *“The licensee is required to foster a safety culture to discourage complacency at all levels in the organisation. This is particularly important in decommissioning, where the facility’s configuration is undergoing continual change.”* Another major change is the increase of external workforce present at the facility: *“Decommissioning actions may involve additional organisations, including contractors and subcontractors who might not be familiar with the facility and the management system of the licensee.”* This implies that the facility knowledge possessed by long-term employees becomes very valuable, especially because the configuration of an old plant may not be fully documented: *“Although new skills might be required for decommissioning, attention should also be given to preserving the knowledge of key personnel who are familiar with the facility from its operational stage.”* It is essential to pay attention to motivating the remaining long-term and knowledgeable employees, who have joined the organisation in order to produce energy, and may have very diverse emotions after the plant has been shut down and the procedures and roles adjusted towards decommissioning.

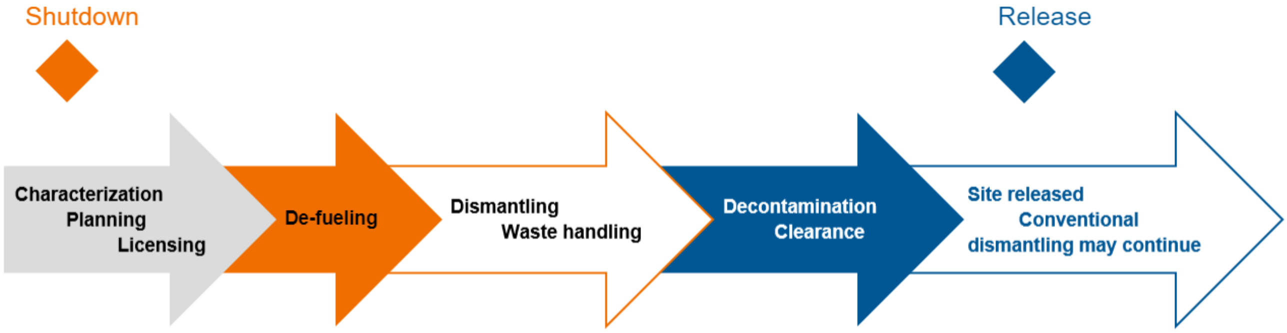

Figure 10. Simplified phases of decommissioning [Gotcheva et al. 2021].

For preserving and developing the safety culture, a safety culture development plan was written in 2016 and has been maintained since then. In 2017–2018, a comprehensive FiR 1 specific safety culture assessment was conducted by VTT's own independent experts, including also interviews of the major stakeholders such as the Finnish Radiation and Nuclear Safety Authority STUK and the Ministry of Economic Affairs and the Employment (MEAE) [Ylönen & Airola 2018]. Recently, an annual safety culture survey [Viitanen et al. 2021] has been taken into use, to follow up and to measure the safety culture development.

3.2 Preserving facility knowledge and complementing expertise at FiR 1

The organization of the FiR 1 with its safety responsibilities continues to operate during the permanent shutdown and decommissioning phase under the supervision of the Finnish Radiation and Nuclear Safety Authority STUK. In August 2021, STUK approved the new administrative rules for FiR 1, transferring the organization to the decommissioning phase. VTT has taken into account the requirements of the changing operating environment in the decommissioning phase when organizing radiation protection, emergency preparedness, site security and nuclear safeguards. In particular, new procedures have been created to manage safety and quality in subcontracting. In practice, the new administrative rules are applied e.g. in the work order procedure for safety-critical work at FiR 1.

While VTT has retained all personnel of the operating organization, a few key recruitments have been important in strengthening the competences in waste management planning, licensing framework knowledge and radionuclide measurements. The project organization is relatively small and involves all staff of the previous, still maintained part-time operating organization. As previously mentioned, in 2017–18, VTT carried out a safety culture assessment [Ylönen & Airola 2018] by VTT's own independent experts. The assessment confirms that the organization is competent and committed, but that the systemic uncertainties (like time and cost) can jeopardize the safety culture by creating tension between economic and safety aspects. In addition, the assessment recommends VTT's organization to put additional attention on competence and information management. A follow-up study was conducted in 2021 [Viitanen et al. 2021] with the conclusion that in general, the safety culture in the decommissioning project was experienced to be at a fairly good level and the majority perceived that it had improved. However, some of the same worries remain as in 2018. Based on the findings, VTT has defined new concrete development actions.

3.3 Licensing of FiR 1 for decommissioning

3.3.1 Overview

FiR 1 is the first nuclear facility to be decommissioned in Finland. Despite several orders of magnitude smaller fuel, dismantling waste and activity inventories compared to power reactors, similar licencing procedures apply. FiR 1 decommissioning has indeed become a pioneering project not only for VTT but also for authorities and domestic nuclear power utilities which will face decommissioning issues in the coming decades. Internationally, previous experience is available. Several reactors of corresponding type have been decommissioned for instance in Denmark and Germany, and experiences from those projects are utilized in the decommissioning of FiR 1.

3.3.2 Finnish regulatory framework for use of nuclear energy and radiation

In Finland, two Government ministries (Ministry of Economic Affairs and the Employment, MEAE, and Ministry of Social Affairs and Health, MSAH) carry a shared responsibility on nuclear and radiation related matters (see Figure 11). The roles are defined in the Radiation Act, while nuclear energy matters are specifically regulated by the Nuclear Energy Act. STUK (Radiation and Nuclear Regulatory Authority) operates under the performance guidance of MSAH and is responsible for the technical supervision of both nuclear and other radiation activities. MEAE is the supreme authority for nuclear energy matters and has a direct supervisory role concerning societal and political aspects of the use of nuclear energy.

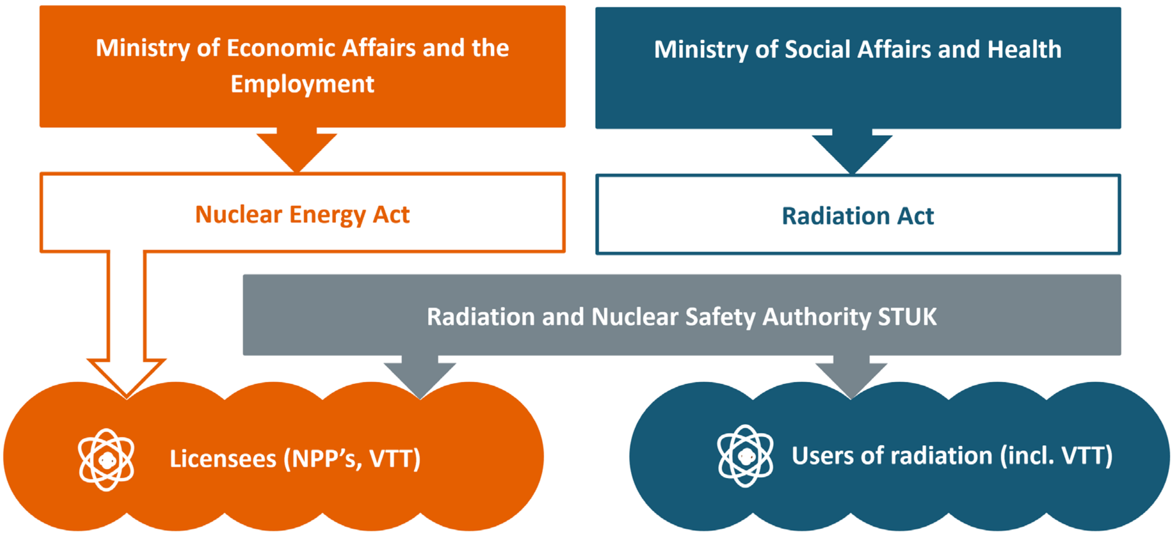

Figure 11. Illustration of the Finnish regulatory framework for use of nuclear energy and radiation.

In the following, we summarize the main steps towards fulfilling the prerequisites for the nuclear decommissioning licence for FiR 1. Actual licensing is preceded by an Environmental Impact Assessment (EIA) for decommissioning. The main prerequisite for the licence itself 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* [Nuclear Energy Act 1987].

3.3.3 Environmental Impact Assessment in 2013–15

Soon after the shutdown decision and before applying the decommissioning licence for FiR 1, VTT carried out an Environmental Impact Assessment (EIA) for decommissioning, as required by the Act on Environmental Impact Assessment Procedure [Act on EIA 2017]. The EIA procedure generally aims to ensure that the environmental impact is evaluated and taken into account on a consistent basis in planning and decision-making. Another objective is to increase the awareness of citizens and improve their opportunities to participate in and influence project planning. Decisions regarding the actual project will not be made, nor licensing matters decided, during the EIA procedure.

The EIA procedure involves programme and reporting stages. The EIA programme is a plan for the implementation of the EIA procedure and for the topical survey reports. The resulting EIA report presents the project's features and technical solutions, along with a consolidated assessment of the project's environmental impact, formed as a result of the assessment. The EIA procedure is an open process, in which individuals and other interested groups are invited to participate and present their views to the project's coordination authority, the MEAE, to VTT as the responsible party, or to the consultant. A stakeholder group was assembled to support the EIA procedure. The group assisted in the exchange of information between the parties responsible for the project, the authorities, and other stakeholders. The monitoring group convened twice during the EIA’s execution stages.

Two main decommissioning alternatives were considered:

- ALT1: Immediate decommissioning
- ALT2: Delayed decommissioning

Continued operation of the research reactor, in a situation in which it is not decommissioned, was considered as the so-called zero alternative. In this case, decommissioning and other nuclear waste management measures would take place at a later date.

As a result of the EIA procedure, it can be concluded that the VTT reactor decommissioning project will not have a significant environmental impact. The MEAE gave the final statement on the EIA report in February 2015. A few stakeholders provided the Ministry with their remarks on the report to be accounted for in the detailed decommissioning planning.

3.3.4 Planning phase

The Finnish licensees shall maintain their nuclear waste management plans over the whole operating lifetime of their reactors. The plans have also an economic dimension as each licensee is obliged to contribute accordingly to the Nuclear Waste Management Fund managed by the MEAE. The fund reimburses costs gradually to the licensees following the completion of their decommissioning duties.

Significant refinement of the nuclear waste management plans is required when the nuclear facility is really approaching decommissioning. This planning has been further developed in the Environmental Impact Assessment (EIA) for FiR 1 decommissioning that was carried out by VTT in 2013–15 (reports only in Finnish and Swedish available at [MEAE 2014]).

In the first phase, a relatively broad range of underlying questions had to be answered, related to specific issues of decommissioning a TRIGA type reactor. For instance, Finnish NPP’s do not contain irradiated graphite, aluminium and some research materials that FiR 1 will yield into the Finnish nuclear waste management system. Therefore, VTT conducted a literature survey [Carlsson et al. 2014] to collect information on the chemical behaviour of irradiated aluminium and graphite under expected final repository conditions, international practices concerning the management and final disposal of irradiated aluminium and graphite, and experimental techniques for determining the chemical form (organic or inorganic) of the ^{14}C released from graphite waste. This study is represented by one of the grey boxes in Figure 12. In general, this and the many other studies shown in the lowest layer of the figure were completed in the EIA phase or soon thereafter, providing the fundamental basis for the second grey layer.

3.3.5 License application in 2017, license in 2021

The second grey layer in Figure 12 represents more technical design documentation required for composing the preliminary decommissioning plan and for updating all other facility documentation for the decommissioning phase ("Supporting documents to STUK", as required in the Nuclear Energy Decree [Nuclear Energy Decree 1988] and marked in blue). STUK reviewed the technical and administrative documentation and gave their safety assessment on decommissioning in April 2019 (and updated it in April 2021). In parallel, MEAE was reviewing the actual application and its appendices (orange; a public set of documentation available at the web pages of MEAE [MEAE 2021]), making sure that VTT's plans and contractual arrangements are mature enough for the decommissioning and nuclear waste management to take place in a reliable manner until the very end.

The review time of VTT's application for FiR 1 decommissioning was relatively long, about four years. The main reason is that VTT's nuclear waste management solutions are based on commercial contracts, which were not yet in place upon the submission of the licence application. An essential complement of the original application was VTT's letter to MEAE in spring 2020. In the letter, VTT reported that a comprehensive contract on decommissioning services had been signed in March 2020 between VTT and Fortum Power and Heat Oy (Fortum), covering dismantling of FiR 1 and all necessary nuclear waste management services. We describe the contract in more detail in Section 3.4. The contract eliminates the long-standing uncertainties, which were mitigated by VTT by pursuing alternative waste management solutions in parallel (e.g., preparing for interim storage for SNF at a Finnish NPP in case USA would not have been able to receive it in the near future). A consolidated schedule, taking also into account the removal of the spent fuel at the end of 2020, is presented in Figure 13.

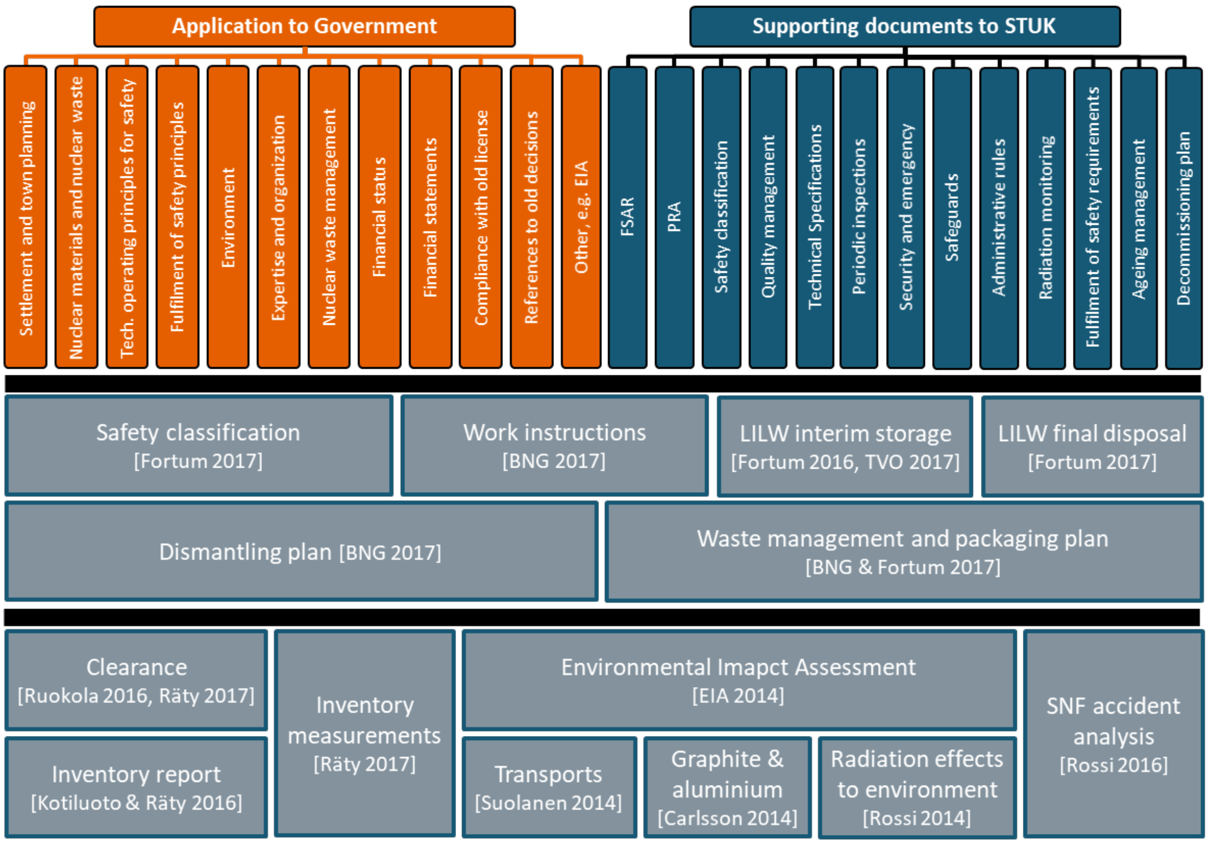

Figure 12. The structure of VTT's licence application, following the Nuclear Energy Decree. The actual public application and its appendices (titles shortened) are illustrated in orange. The more detailed technical documentation was reviewed by STUK and is illustrated in blue. In the Environmental Impact Assessment phase and during the following preliminary planning phase, preceding the application, VTT and contractors carried out several studies illustrated in grey.

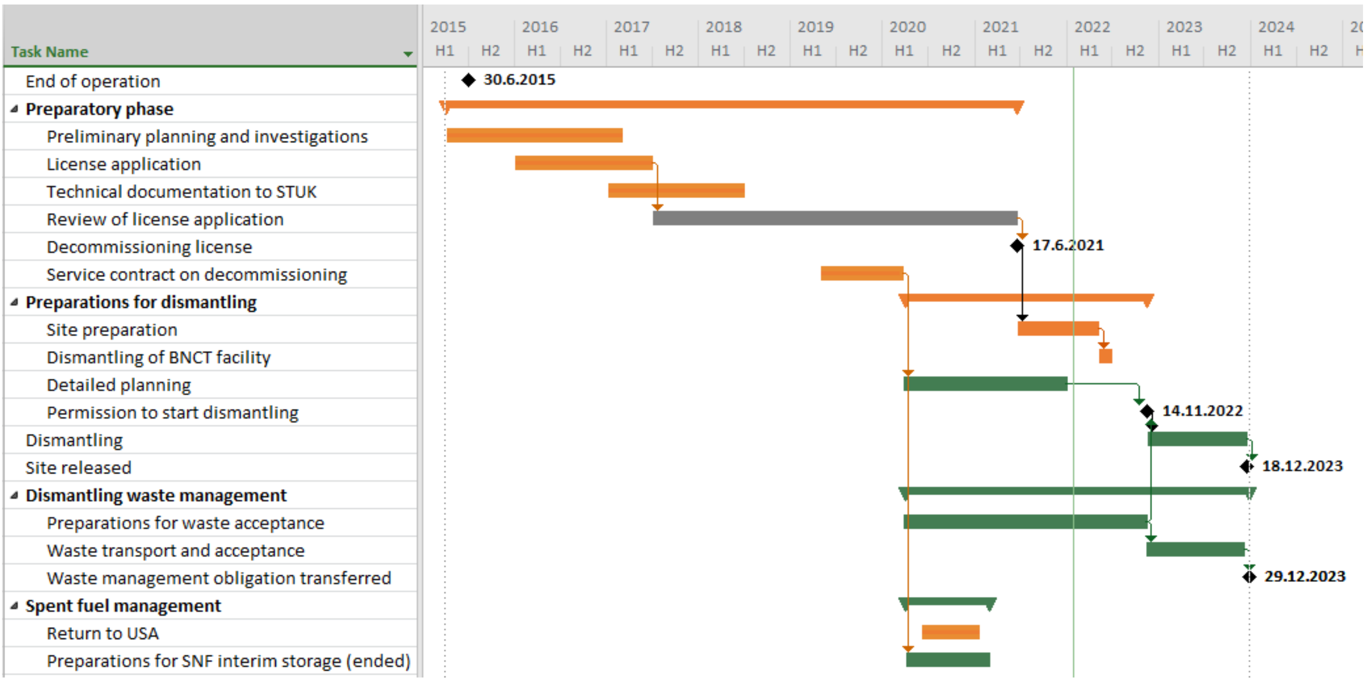

Figure 13. Schedule for FiR 1 decommissioning after shipping of the spent fuel and terminating interim storage preparations for the fuel as obsolete. Green bars represent tasks that are mostly covered by the service contract for decommissioning.

3.4 Contracting

Essential for the FiR 1 decommissioning project, and for fulfilling the prerequisites for the decommissioning licence, is the comprehensive contract on decommissioning 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 adjacent radioactive materials research laboratory (called OK3). An industrial partner taking responsibility of the waste management is absolutely necessary for a research organization like VTT, who does not have own nuclear waste management facilities. Presently, there is also no national option for such mid-scale nuclear and radioactive waste stream (tens or hundreds of m^3) in Finland, only for small radioactive waste streams from industry, medicine and research.

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, on the basis of which the procurement unit (buyer) and the tenderers undergo negotiations in order 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 projects' 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) procedures in selecting the EIA and dismantling planning consultants in 2013 and 2016.

4. Anticipating decommissioning in research reactor design, construction, operation and maintenance

As the FiR 1 research reactor was built already in 1960's, the international and domestic requirements and regulations were much different compared to the current situation, i.e. much lighter. For instance, the current IAEA general and specific requirements take decommissioning very much into account already in the early stage of the life cycle of a nuclear installation, e.g. by requiring a preliminary decommissioning plan.

As far as FiR 1 is concerned, the TRIGA reactor design itself does not pose any specific problems for dismantling of the SSCs. However, lack of detailed knowledge on the used materials and their specifications has been noted. This concerns, for instance, the material specifications of the graphite, aluminium and steel. The mechanical construction specifications of the concrete of the biological shield were exceptionally well documented by the Finnish experts at the time of construction [Pihlajavaara & Pihlman 1961, 1962] but still it turned out later that for activation evaluation, some additional composition data was needed. In particular, europium isotopes ^{152}Eu and ^{154}Eu were identified as the radionuclides producing the highest contribution to total activity in concrete, although the Eu concentration is only about 2 ppm [Koskinen & Lindqvist 2014] but the neutron capture cross sections are large.

Following the current requirements, the materials would have been documented in much more detail, and material samples from each production batch would have been stored. The current international requirements pay much more attention also on knowledge and data management. For instance, the detailed use and operating history of the FiR 1 TRIGA beam tubes has not been very well documented or the data management has failed to preserve this data, including the details of the used equipment inside the beam tube, especially in the early history of FiR 1.

Paying attention on detailed documentation of the reactor design and construction, as well as operating history and plant modifications, cannot be too much emphasized. Today all planning work and most of the communication takes place in the digital world. Therefore, thousands of paper documents have been scanned to digital format, mainly pdf. More than five hundred of these have been listed in the FiR 1 dismantling document system, which has been shared with the planning and execution phase contractors.

Early and comprehensive computational characterization of radionuclide inventories has been highly valuable for all later planning. We strongly encourage decommissioning operators to invest sufficiently to that important phase early on. Also, we have seen that the demand for characterization remains high over a long time, to which VTT has responded with continued competence building in both activation modelling and measurements.

Reflecting to new build projects, collecting inactive reference materials of the reactor structures is very essential so that activation calculations can be performed with reliable input data. Validating the calculated estimates with measurements also require systematic development of the measurement methods. International intercalibration exercises are an example of valuable method development. This also provides an opportunity to systematically document the best methods.

5. Lessons learned

The licensing phase of the project has 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 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.

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 end-point 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. Summary

FiR 1 served as a central place of training and research for over 50 years, educating an early generation of nuclear energy professionals who were needed to start four power reactors in 1977–1980, all reactors still operating with very high capacity utilization rates. Now it serves as a pilot also in the decommissioning phase.

It is obvious that there is significant potential to optimize the economy of decommissioning of standard type nuclear facilities, like TRIGA research reactors or common types of NPP's, by using a specialized decommissioning organization, which can multiply the knowhow, or the product. Still, as a research organization with a single nuclear facility, VTT has decided to build own relevant competence and capitalize on the accumulating experiences. To this end, VTT has launched a decommissioning business ecosystem *dECOmm* to develop new services to the international decommissioning market together with several Finnish companies [VTT 2020].

The *dECOmm* ecosystem's research project supports companies' own projects and includes building information models (BIM), virtual and augmented reality, radiation transport and dose modelling, artificial intelligence, human factors, operating and licensing framework as well as innovation ecosystems and ecosystemic business. Conversely, experiences from the company projects will be exploited as valuable input for research. FiR 1, while being a nuclear facility, can provide a small-scale, easy-to-access test bed for the developed technologies. By involving a spectrum of companies with different backgrounds, all partners learn about the specifics of the nuclear domain, like regulations and quality requirements. Important in decommissioning is to understand where and when requirements can be relaxed.

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