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Radioactive Waste Management Committee

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Foreword

This report represents the result of the engagement of the Nuclear Energy Agency (NEA) Expert Group on Robotics and Remote Systems in the nuclear back-end during its second mandate, between 2022 and 2024. The goal was to pursue the inclusive and bottom-up initiative to get closer to the end-user perspective and to propose guidance on the topics identified at the end of the first mandate.

The report focuses on three key areas of interest as a result of the work summarised in the first NEA report "Status, Barriers and Cost-Benefits of Robotic and Remote Systems Applications in Nuclear Decommissioning and Radioactive Waste Management" (NEA, 2023), namely aspects related to: 1) the regulation and licensing of robotics in nuclear energy, 2) the development of a framework for benchmarking and 3) the development of a methodology for comparative evaluation of cost/benefit of robotics and remote systems implementation. The guidance and considerations in the report are based on cases studies collected from experts from various member countries. This report was approved by the Radioactive Waste Management Committee (RWMC) on 22 September 2024 and prepared for publication by the NEA.

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Table of contents

Figures

Tables

List of abbreviations and acronyms

AMA	Ageing management activities
AMP	Ageing management programmes
AMR	Ageing management review
ASME	American Society of Mechanical Engineers
CAPEX	Capital expenditures
CAR	Canadian Aviation Regulations
CATT	Canadian Adversarial Testing Team
CBA	Cost-benefit analysis
CDM	Construction, Design Management
CPD	Co-operative Programme on Decommissioning
DCSS	Dry cask storage system
DSS	Dry Storage Systems
EDF	Electricité de France
EGRRS	Expert Group on Robotics and Remote Systems
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
FOAK	First-of-a-kind
FoF	Force on Force
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HLW	High-level waste
IAEA	International Atomic Energy Agency
IDN	International Decommissioning Network
IFE	Institute for Energy Technology (Norway)
ILW	Intermediate-level waste
ISFSI	Independent Spent Fuel Storage Installations
LLW	Low-level waste
MAPS	Managing Aging Processes in Storage
MASE	Italian Ministry of Environment and Energy Security
MER	Manipulation and Environmental Robotics
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission (United States)

NRF	Nuclear response force
OEL	Optical Engineering Ltd
ONR	Office for Nuclear Regulation (United Kingdom)
OPEX	Operational expenditures
RD&D	Research, development and demonstration
RTT	Robotic Technologies of Tennessee
RWMC	Radioactive Waste Management Committee (NEA)
SG	Steam Generator
SL	Sellafield Ltd
SNF	Spent nuclear fuel
SONGS	San Onofre Nuclear Generating Station (United States)
SSC	Structures, systems, and components
TDGR	Transportation of Dangerous Goods Regulations
TLAA	Time-limited ageing analyses
TRL	Technology Readiness Level
UMM	Uranium mines and mills
US DOE	United States Department of Energy
VLLW	Very low-level waste
WPI	Worcester Polytechnic Institute (United States)

Executive summary

More than 30 countries have pledged to triple their nuclear capacity to mitigate climate change since a first declaration to this effect was made at the United Nations Climate Change Conference (COP28) in 2023. According to the pledges, new reactors and supporting facilities will be added to the current global nuclear fleet, which currently amounts to more than 410 reactors in operation. As of 2025, only around 20 plants have been fully decommissioned (IAEA Power Reactor Information System, see https://pris.iaea.org/pris/home.aspx) and several hundreds of plants are estimated to be shut down and decommissioned in the next decades. This anticipated increase in nuclear capacity and upcoming decommissioning will ultimately create more radioactive equipment and waste of different types to be dismantled, sorted and managed in a safe way.

Meeting the future needs of the back-end will require the availability of a dedicated workforce as well as the optimisation of the tasks and schedules due to competing projects and sites. In this context, the adoption of robotics and remote systems could be a game changer.

This report aims to support further implementation of robotic and remote systems (RRS) in the nuclear back-end in order to minimise human exposure to the dangers and risk associated with decommissioning and nuclear waste handling, as well as to improve the nuclear back-end management through innovation.

The second report of the Expert Group on Robotics and Remote Systems (EGRRS) reflects the programme of work of the group's second mandate, which was structured into three work streams:

- Licensing – Perceived as one of the key challenges in the implementation of new technologies in nuclear environments compared to other industries.
- Benchmarking - Seen as a key enabler to find synergies among nuclear operators and accelerate the transition to remote systems to reduce risk to operators.
- Cost-benefit analysis - Needed as a systematic approach to evaluate different options and identify or build business cases for RRS implementation.

The licensing workstream aimed at gaining insights on opportunities for improving this process by sharing areas of good practice between different countries. The collection of 10 international case studies and additional group discussions made it possible to identify:

1. Enablers of innovation used to secure safe and cost-effective nuclear operations in the nuclear fuel back-end;
2. Blockers (or perceived blockers) of innovation in the regulatory permissioning/licensing process.

Good practices were identified, such as:

- Lessons learnt exercises involving regulators and licensees, which could provide a positive way to reflect on challenges and opportunities emerging from licensing.
- The necessity to have long-term and appropriate engagement strategies between stakeholders.

- The use of inactive mock-ups (including digital twins) or active demonstrators, which could provide a good opportunity to de-risk the final licensing of a full-scale plant involving innovative solutions.
- The implementation of a robust defence in depth to provide a positive means by which solutions imported from other less hazardous industries can be safely deployed in the nuclear sector.
- Upfront work on the safety case to consider safety in parallel to the design from early stages of development.

The benchmarking workstream was conceptualised to accelerate the transition from manual labour to RRS. In fact, one of the primary challenges to the adoption of innovative technologies is to prove the level of readiness and reliability of the RRS, and to collect user experience data. This information is required to support regulatory bodies, decision makers, programme managers and project leaders in their assessment and decision processes. The EGRRS believes that one of the solutions is to build a benchmarking database, hosting data to assess and verify the different robotic and remote systems independently.

Applying traditional benchmarking approaches to the nuclear industry, however, is challenging due to the absence of defined "reference cases" in this highly specialised field. Furthermore, each country and site within the nuclear sector operates under distinct interpretations of international regulations, unique local cultures, and faces diverse technical challenges. Finally, there are no two similar back-end sites, as all of them carry specificities and unknowns linked to their history. This inherent diversity renders the conventional benchmarking methodology impractical. To overcome these challenges and tailor benchmarking to the back-end nuclear domain, the proposed approach involves circumventing site-specific differences and focusing on the fundamental tasks associated with decommissioning and waste handling.

As a starting point, the EGRRS analysed the various tasks and works that could be performed by robots or remote systems and found four main categories.

- Mapping/measurement and investigation – to monitor or measure radiation of various kinds, to allow a better understanding of the physical conditions of the plant.
- Decommissioning works – dismantling or decommissioning activities.
- Material and waste handling – segregation and packing waste and other subtasks in the field.
- Revision/service – tasks that are within the maintenance field.

The EGRRS also established a grading system that assesses whether a system has been demonstrated or extensively used with lessons learnt available, and theorised a step-wise methodology to allow for fair and balanced assessments from experts, with the possibility for solution developers to reply to criticism and requests before data are uploaded into the system.

The EGRRS hopes to make this concept a reality and will strive to further detail the business plan and draft the technical requirements for the database in the next mandate period.

The cost-benefit analysis workstream emerged in response to the lack of costing data, which made it difficult to justify investment in new technologies deviating from the status quo. A cost-benefit analysis (CBA) sums the potential rewards, or benefits, expected from each action or decision, and summarises the total cost assigned with taking that action or decision. The outcome of the analysis determines whether the decision is financially feasible or if another direction should be investigated.

A specificity of the nuclear back-end is the fact that there are no traditional "returns on investment" in the form of financial profit. The main economic benefits to an investment would be primarily the value of generated safety, saved costs and the value generated by the reuse of a site, if any. Another specificity lies in the complex nature of most back-end sites. In fact, while establishing the list of costs throughout the entire life cycle of a back-end project, including radiological protection, waste management, incident and accident mitigation, might be possible, these projects typically deal with unexpected deviations and complications which make it very challenging to anticipate an accurate and comprehensive financial assessment of all the costs. A comparative CBA, subtracting the common unknowns from all the different scenarios, and fixing the end-state, is a pragmatic way forward to justify the use of RRS even if not all cost components are known.

The EGRRS aims to transform those concepts into applicable structures and tools for the nuclear back-end in the course of future mandates. The EGRRS is convinced that implementation of robotics and remote systems will have a significant positive impact on the nuclear back-end management, making it possible to meet the challenges posed by the increasing number of nuclear projects foreseen in the upcoming decades.

1. Introduction

There are currently about 410 nuclear reactors in operation around the world (WNISR, 2023; IAEA PRIS, 2023). By 2050, it is estimated that around 200 of them will be in active decommissioning or have already been decommissioned.

As governments around the world identify the measures needed to mitigate climate change, it appears that the development of nuclear energy will play a key role by delivering low-carbon energy.

Indeed, since 2023, over 30 countries have pledged to triple their nuclear power capacity. The pledges include both conventional nuclear power plants and advanced small modular reactor technologies. This anticipated increase of nuclear energy will come with an expansion in the need for management of the nuclear back-end. Power reactors and research and fuel cycle facilities will eventually need to be dismantled, while spent fuel and radioactive waste will need to be sorted, handled and disposed of safely.

Meeting the future needs of the back-end will require a dedicated workforce as well as the optimisation of the tasks and schedules of competing projects and sites. In this context, robotics and remote systems could provide significant support, notably by minimising human exposure and the dangers and risks associated with decommissioning and nuclear waste handling, but also by opening other fields of application that could improve back-end operations, such as routine radioactive monitoring over large areas.

Following the work conducted during its first mandate, which partly consisted in identifying barriers to implementation, the NEA Expert Group on Robotics and Remote Systems (EGRRS) structured its programme of work intro three work streams:

- *Licensing of innovative technologies*. The results of the survey conducted during the first mandate showed that licensing is often perceived as one of the key challenges in the implementation of new technologies in nuclear back-end environments. One of the goals of the workstream was to investigate this perception through case studies reflecting different regulatory frameworks, different perspectives, different types of technology and different technological readiness levels.
- *Benchmarking*. The same survey highlighted the lack of non-commercial technical data as well as limited lessons learnt from failed implementations. This lack of data increases the risks in the decision-making processes and creates reluctance to adopt. The expert group theorised that a database hosting benchmarked technical RRS data would be a key enabler, also making it possible to find synergies among nuclear operators and eventually accelerating the transition to remote systems.
- *Cost-benefit analysis.* In conjunction with the lack of technical data and honest lessons learnt, it was found that building a business case for RRS was difficult, in part due to the complexity of back-end projects, which limits financial foresight. The expert group found the need to provide a systematic approach to evaluating different options and identifying or building business cases for RRS implementation and tried to apply it to real-life examples.

The work of the EGRRS presented in this report aims at supporting the implementation of robotics and remote systems in the back-end.

References

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2. Regulation and licensing of robotics and remote systems

2.1. Introduction

In the first phase of the EGRRS, one of the key barriers for the deployment of robotics and remote systems in the nuclear fuel back-end was related to their "licensing and regulatory process" (NEA, 2023). The main impact of this was on project schedule and costs.

In this context, one of the three workstreams in the second mandate of the EGRRS focused on the regulation of robotic and remote systems to gain insights on opportunities for improving this process by sharing areas of good practice between different countries. To achieve this purpose, the need to understand different perspectives was recognised, including those from:

- nuclear regulators;
- nuclear operators;
- research centres;
- universities;
- manufacturers and engineering companies.

The main objectives agreed for the workstream on regulation as defined during the EGRRS-3 plenary meeting were:

1. to identify enablers of innovation used to secure safe and cost-effective nuclear operations in the nuclear fuel back-end;
2. to identify and tackle blockers (or perceived blockers) of innovation in the regulatory permissioning/licensing process.

The remainder of this chapter is organised as follows. Section 2.2 presents the **main learnings** from the test cases, presented in Appendix 1 and the discussions in the EGRRS plenaries. Section 2.3 provides an **overview of a process** which, recognising the lessons learnt, provides visibility to all relevant stakeholders of the key enablers for a targeted licensing process and raises awareness of different roles and perspectives. Section 2.4 draws some **conclusions** on the licensing and regulation process for robotics and remote systems.

2.2. Lessons learnt from the test cases

The lessons learnt presented in the following subsections are based on 10 test cases reported in Appendix 1. The aim of the test cases was to provide a good representation of the various applications and capture the perspectives of different stakeholders involved in the working group. The scope of the test cases included:

- mature applications ready for deployment (e.g. including commercial off-the-shelf technology used in other sectors);
- novel applications in the initial feasibility study phase (e.g. including bespoke solutions or extension of commercial off-the-shelf solutions in new settings);
- cutting-edge solutions at very early stages of development (e.g. developed by universities or research centres).

2.2.1. Blockers to the licensing of a robotics and remote system solution

Some of the common blockers emerging from the test cases in Appendix 1 and in the discussions in the EGRRS plenaries are:

- Engineering substantiation: Some of the robotics solutions proposed for a nuclear application are currently used in various industrial applications (e.g. automotive manufacturing). A challenge that was identified in some of the test cases relates to the evidence needed to support a nuclear application compared to other industries. This very much depends on the regulatory framework of the country and the regulatory context. There is a consensus that the main driver to determine what is proportionate is the nuclear safety consequence. Furthermore, major application challenges have been observed with respect to cybersecurity (EPRI, 2024). Opportunities could be explored for further international work on clarifying the expectations, e.g. developing dedicated standards or guidance, and exploring the approach taken in other industries and the relevance in the nuclear context.
- Licensing for specific applications: Ideally it would be helpful for a robotic solution to be licensed for a wide range of nuclear applications. In practice, experience from the test cases shows that the context of the application is important as the nuclear safety consequences can vary significantly. Also, different applications can have diverse requirements e.g. in terms of normal/abnormal operation and maintenance. Opportunities could be explored to adopt an approach similar to the one taken for smart devices (IAEA, 2020; 2023), where a generic substantiation of a solution can be qualified by clearly identifying the justification envelope (or bounding safety case) and can help targeting the effort in case of a new proposed application.
- Lack of understanding of final application: This represents a key challenge for lower technology maturity level solutions under development by research centres and universities. It is often challenging for these stakeholders to fully appreciate at early stages the requirements from prospective end users and the regulatory expectations/legal obligations. Opportunities could be explored to establish national fora where various stakeholders can meet and discuss opportunities in a positive environment.
- Difference in terminology: This represents a challenge for many stakeholders as the definitions of some of the key terms related to robotics can be different depending on the stakeholders. This may hinder effective communication, and in some cases, create unnecessary burden. An example is in the definition of artificial intelligence and its difference with respect to machine learning. Opportunities could be identified to clarify this e.g. as part of an international report or journal paper produced by EGRRS presenting various examples of AI-based systems.
- Late engagement: some regulators highlighted the hesitancy of licensees to engage at an early stage of development. Some of the blockers in this regard could be due to the lack of sufficient information at early design stages to clarify perspectives (including regulatory expectations and areas of focus for licensing) or the fact that

a licensing team is not yet ready for a formal engagement. In some cases, this could also be due to the lack of clarity of the regulatory expectation on innovative solutions. In discussion with the licensees, there was a perception that some of the information available at early stages might not be relevant for the regulator or the value added of the engagement at early stages with the regulator could be limited. Opportunities could be explored to identify key milestones and deliverables in the design and licensing of a novel solution to clarify all perspectives. Because of resource challenges (both on the regulator and licensee's sides), suitable prioritisation should be given e.g. to projects where the uncertainty/novelty of the solution is higher, as well as where the potential benefit is more prominent.

- Risk-averse approach of the regulators: Although it is recognised that the nuclear regulator generally takes a conservative approach in dealing with new technologies if there are uncertainties on their previous use, the test cases and discussions in the EGRRS plenaries seem to suggest that this is a reflection of a sound nuclear safety culture rather than a bias against new technology. The group recognised that the number of test cases considered in Appendix 1 is limited and there is a need to continue considering areas where regulation can hinder innovation. In the discussions, there was also a recognition of the importance of regulator staff having early visibility and targeted training on new technologies, to be able to effectively regulate their applications in nuclear.

- Lack of standardisation: This aspect is clearly challenging at early stages for most innovative solutions. Some of the applications discussed with universities and research labs involve unstructured/changing environments, increasing unpredictability, and changing boundary conditions. Other applications offer more theoretical challenges (e.g. stochastic/probabilistic in path determination). The regulatory expectation in this case may not be consolidated because of the lack of a real need in applications. At this stage, no consensus is captured in standards or other international guidance. Opportunities could be identified to understand which areas to focus the effort on in the short/medium term.

2.2.2. Enablers of the licensing of a robotics and remote system solution

Some of the common enablers that emerged from the test cases in Appendix 1 and the discussions in the EGRRS plenary are:

- Defence in depth: An effective implementation of defence in depth in the system engineering design could provide a significant advantage in terms of reducing the safety claim on the robotic solution. This can be achieved by designing a resilient architecture where different functions are allocated to various engineered solutions to support safe operation of the system as a whole. The function allocation process should go beyond simply replacing the operator by a robot and should design the system architecture to suitably account for the specific features of the robotic solution involved. This robust engineering approach could also help by mitigating some of the hazards associated with unplanned behaviour of the robot (e.g. due to sensor failure, incorrect programming, misconfiguration or human error in operation). While this approach may not always allow full exploitation of the functionality of an innovative solution (e.g. safety claim allocated to an interlocked barrier rather than the complex software functionality of the robotic system), this has the advantage of providing additional resilience from a nuclear safety perspective and could also mitigate against the risk of cyberattacks.

- Overall safety argument: One of the main challenges in nuclear fuel handling is associated with the operators potentially being exposed to radiation dose. The use of robotics solutions has the potential to take the human element away from the risk as well as potentially delivering tasks that cannot be done manually (e.g. access to high-radiation areas, or complex tasks in contaminated areas). Although the use of robotics can clearly introduce new challenges, there is an argument that, by not using the robotic systems, some risk reduction activities could be significantly delayed. The overall safety case should consider this aspect in determining what is the most appropriate solution.
- Functional hazard approach: The effort in the robotic substantiation could be targeted by identifying the hazardous function failure conditions for the robotic solution. The substantiation can then determine and mitigate the nuclear safety consequences if such failure conditions should occur. The functional hazard analysis approach is used in the aerospace and automotive sectors when developing safety critical systems which typically employ software (SAE, 2023), and could be adapted for use with applications in nuclear energy.
- Multi-discipline engagement: The design, licensing and operation of robotic solutions requires varied specialist knowledge, including instrumentation and control, human factors, cybersecurity, and mechanical engineering. It also needs to recognise the implication in terms of the overall safety substantiation. Recognising this need at an early stage could provide a benefit to identifying a solution that delivers the cost benefit expected from the project in the context of the regulatory requirements.
- Skills and open mindset: The use of robotic solutions may require new skillsets which could take time to build both in industry and at the regulators. Having an ownership programme (person or group responsible for the implementation) at nuclear power plants has proven to be crucial for the successful application of robotics. Additionally, it was observed that use cases and value tend to grow after purchasing a robot (EPRI, 2024). Horizon scanning of new technologies could provide an effective way to understand early on when training, awareness or new research could be beneficial. National programmes should be encouraged with the aim of extending the use of new technology in the nuclear sector, engaging all stakeholders (including regulators) to understand the challenges and opportunities offered by new solutions and where they can be used best in a nuclear environment.
- Mock-up/trials/active demonstrators: There is a consensus that testing new solutions in an inactive environment or a scaled down facility (including in a control lab with realistic radiation conditions) where the nuclear safety risk is reduced represents a positive way of building confidence in the design solution. This could also create opportunities for an effective engagement with the regulator at early stages of design/investment decisions for the full-scale facility. Where appropriate, relevant experience from robotics applications in non-nuclear industries could also be considered as an initial assessment of the potential of the technology.
- Lessons learnt: Learning from experience is identified by multiple stakeholders as an area of good practice, particularly where innovation is involved. Although this process is often done independently by the regulator and the licensee, there could be an opportunity to more systematically run joint lesson learnt sessions between regulators and operators to reflect on the engagement following a complex permissioning process and feed into the discussions regarding new projects.

Opportunities could be sought to learn from the experiences of non-nuclear industries.

2.2.3. A note on the implications of autonomy in robotic system

Increasingly autonomous systems pose new kinds of challenges for regulators, especially around guaranteeing safety. However, they may also offer safety benefits which can be enabling.

Real-world, deployable systems are now beginning to incorporate techniques from the autonomous robotics research community that are becoming increasingly mature and robust. At first, these technologies will extend the traditional teleoperated systems to semi-autonomous control paradigms, in which autonomous capabilities are used as "operator assistance technologies" for a human supervisor working with a remote robot. Such paradigms may include "variable autonomy" where the robot can be switched between autonomous behaviours and teleoperated behaviours; "human-supervised autonomy" where an autonomous system plans a motion or action, and the human supervisor inspects this (e.g. in a VR or digital twin) before approving the robot to execute the real action; and "shared control", where a human directly teleoperates a remote robot and the motions are modified by autonomous control algorithms, or autonomous motion planners provide feedback haptic cues to the human to nudge or modify their motions (e.g. to avoid a collision).

Potential blockers: The more autonomous a system is, the less pre-planned is its behaviour, i.e. the less predictable it becomes. This is problematic for robots, since they are motorised systems which can move and interact with surrounding objects and scenes in forceful ways, e.g. a robotic arm deploying a powerful cutting tool. Autonomous robotic behaviours will typically be based on large software libraries (typically combinations of public and proprietary libraries), which will typically be impenetrable to staff of site licence companies and regulation experts. This is true even for systems that use fully explainable, deterministic algorithms, and are not based on machine learning. Such systems must be evaluated and regulated as black boxes to some extent. Furthermore, the human operator is also a complex element of the control loop. Evaluating and benchmarking the performance and error rate of a combined human-software-robot system can be complex and is currently a research topic in its own right.

Mitigations: There are some simple holistic approaches to reassuring safety that can be used and already have been used successfully, e.g. semi-autonomous robotic laser cutting, guided by 3D computer vision, which cut contaminated material in an active hot cell in the United Kingdom in 2017 – see accompanying case study. The robot in this example was contained within a concrete cell, which was much stronger than the robot even if an erroneous motion planning algorithm caused a collision with the cell wall. The system was also contained in a laser-proof/resistant cell, and the laser could be switched on and off by the human operator. Furthermore, a digital twin can be used to show a virtual robot performing a virtual cut on a virtual object, so that the operator can inspect the autonomously-planned motions before approving the real robot to execute them – this is a paradigm called "human-supervised autonomy".

Enablers: In terms of potential enabling factors, consider a robot arm installed inside a glovebox environment. It is easy to code in motion-constraints at a low level, which will prevent the robot executing any motions that would cause a collision with the glass window of the glovebox cell. However, the robot could grasp and pick up an object, e.g. a tool inside this cell. It would then have sufficient reach to poke the window despite such low-level limits to its motions. This is a good example of where advanced autonomous robotics technologies could be introduced to enhance safety. A computer vision system could be used to build 3D models of any objects grasped by the robot. These could be added to a 3D model of the links of the robot arm. Advanced motion planning algorithms could then be used to plan and control the motions of the combined robot and object: i) plan autonomous motions which avoid collisions of grasped objects with the window; and ii) automatically limit any teleoperative motions (controlled directly by a human operator) and prevent any human-controlled motions which risk collision of the grasped object with the cell window. (Note such motion control is non-trivial – e.g. motions of the arm holding a long stick parallel to the plane of the window are allowable, but rotating the wrist so that the long stick points towards the window must immediately result in strong constraints that block dangerous motions). This is a form of "shared control" paradigm, in which the autonomous agent and the human are collaboratively controlling the motions of the remote robot.

2.2.4. Considerations

The discussions of the test cases identified some common themes/questions to consider when developing an engagement strategy for the licensing of a novel robotic solution in a nuclear application:

- When is the licensing of robotics and remote systems in a nuclear environment needed? Are there scenarios where their applications are not creating a nuclear hazard and hence quality industrial solutions (including commercial solutions off the shelf for high integrity applications) are suitable?
- Are aspects like fault recovery, potential secondary waste generation and risk of disclosing sensitive information (e.g. through cyberattacks) considered early in the design and regulatory discussions?
- What engagement approach with the regulator is proportionate for new innovative solutions?
- When is it proportionate to start early engagement? What are the design milestones to target (optioneering, scoping, concept design, detail design)?
- How can value be added from an early engagement (with limited design information available)?
- How the need for regulatory certainty be balanced against the imperative of regulatory independence?
- Is there enough knowledge and experience at the regulatory agency to enable the licensing of novel technologies?
- How can adequate skills be developed on new technology/solutions in the nuclear industry (within regulators, licensees and supply chain)?
- How can various specialist perspectives (e.g. engineering, human factors, safety case) be factored in for a proportionate approach to licensing?
- How can operational aspects (e.g. cybersecurity, fault recovery, maintenance, environment, including resistance to radiation) be considered early in the design and regulatory discussions?
- Are there opportunities to leverage the experience of other non-nuclear regulators?
- Is it possible to accept the disadvantages of the new technology over manual workers just to generate experience with robots in the given work environment?

- How can the perceived short-term disadvantages versus long-term gains of robot implementation be overcome?

The next section will aim to address these points in context.

2.3. High-level process to enable proportionate licensing of robotics and remote systems

This section reflects on the lessons learnt from the nine test cases and aims to provide a graphical representation of key steps from the developer, the licensee and the regulator's perspective.

In developing this flowchart, the key elements considered from the previous sections are:

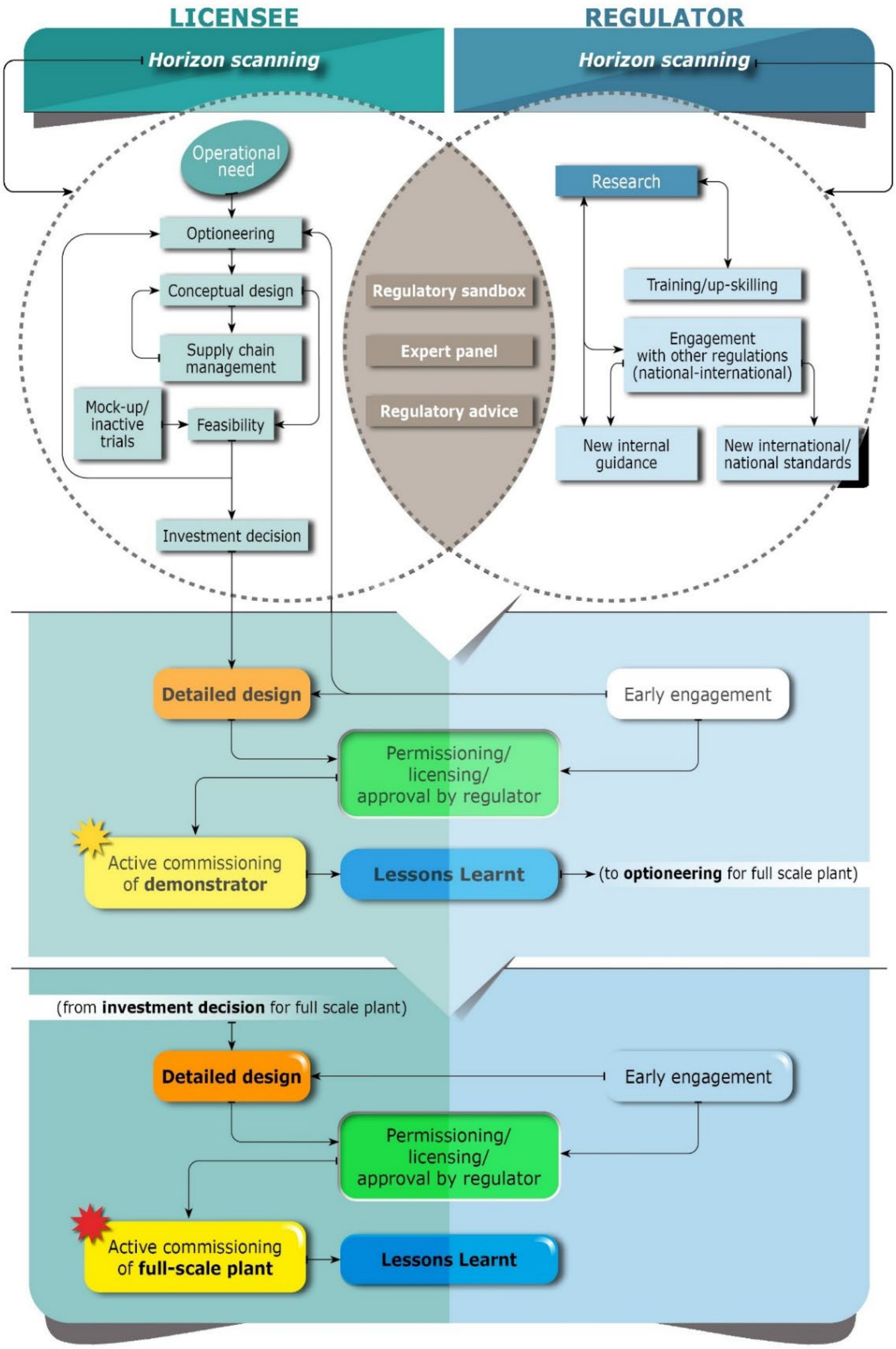
- Factors to consider when planning engagement: The engagement strategy should be proportionate in respect to the specific application. Key factor to consider are complexity, maturity, uncertainty, safety significance, consequences.
- Benefit from an incremental approach: The use of trials and mock-ups in an inactive environment could be a good option to anticipate some of the challenges and building confidence on the approach. The development of active demonstrators (with clear learning purpose and time bounded in duration) could also be effective before applying for licensing of a full-scale active deployment.
- Positive input from an effective horizon scanning: An effective horizon scanning both on the licensee and the regulator side could be beneficial to embrace the opportunities offered by innovation. It could also help upskilling the workforce and identify areas where additional guidance or standards could be needed in the medium term.
- Range of options for engagement: There are a number of engagement options which could be used depending on the specific application and the stage of the design. Besides more formal regulatory engagement, the development of less structured approaches could enable an open dialogue.
- Upfront effort on safety: The focus on safety in early stages of the design can provide a strong advantage in licensing space. While the tendency in initial design stages could be in proving the technical/technological feasibility of an innovative solution, this opens up the risk of creating a bigger effort later on in the project, when the solution needs to meet the regulatory expectations. There is a significant advantage in building in resilience from the beginning of the design, e.g. considering safety as a key factor in option selection, working on the entirety of the system/plant to add defence in depth if appropriate, reducing claims on the robotics solution where possible. Engagement with the regulator on a targeted area at early stages could be appropriate.

The flowchart in Figure 2.1 presents an example of the typical stages in the development and licensing of an innovative solution. The case considered here is of a complex, innovative solution which requires significant regulatory involvement from the initial stages of design. Other less challenging cases could require a less onerous engagement strategy. The key parts of the flowchart are described below:

- The top part relates to the general horizon scanning of both licensees and regulators and is typically carried out to understand opportunities offered by innovation. As part of this, key stakeholders may need to upskill in certain areas or commission targeted research to better understand some technical solutions.

- The top left side summarises the key steps for the developer/licensee to support the investment decision. This process is generally iterative as various stakeholders need to be consulted, including the supply chain involved in various stages (e.g. feeding into feasibility and design). To reduce the uncertainty of a novel technical solution or technology, mock-ups can be used to inform the investment decision. Further activities not included in the flowchart for clarity's sake are research, training and internal guidance development.
- The top right part of the flowchart identified the work carried out in parallel by nuclear regulators, in terms of development of other targeted regulatory guidance (if needed) and engagement with non-nuclear regulators. New international standards might be developed as part of this effort. There could be positive opportunities for regulator and other stakeholders to co-operate in this phase, without compromising the regulatory independence.
- The top middle part of the flowchart identified various opportunities for the regulator and other stakeholders to engage when key design decisions have to be taken and regulatory advice might be helpful for the final licensing of the solution. A few examples are identified in the flowchart, e.g. expert panels, regulatory sandboxes. In this phase, the regulators are not formally assessing a submission, hence engagement with advice and guidance is not affecting their regulatory independence.
- The middle part of the flowchart relates to the detailed design and permissioning of an active demonstrator. In this phase, the regulators must make a formal decision; their independence is therefore essential. The follow-up lessons learnt exercise can be run either independently or with the joined input of the regulator and the operators; this step is important to inform, as appropriate, future projects and the regulatory guidance.
- The bottom part of the flowchart relates to the licensing of a full-scale plant developed from an active demonstrator.

Figure 2.1. Example of a flowchart sketching the process to support licensing of innovative solutions



2.4. Outputs from the regulatory workstream

The key outputs from this workstream on the regulation of robotics and remote systems in the nuclear fuel back-end are captured below:

- **Regulators recognise their role** in enabling the use of innovative technologies to support safe operation in nuclear back-end installation.
- **Regulators appreciate the opportunities** offered by robotics and remote systems in a nuclear environment, e.g. in terms of reducing the risk to operators, making the operation more consistent and speeding up the risk remediation at nuclear legacy.
- **Visibility of final applications and regulatory requirements** would be welcome from developers of cutting-edge solutions like universities or research centres.
- **Leading the engagement** with the relevant regulators after the completion of the investment decision **could create licensing challenges** as some key design decisions for the innovative solutions are taken at early stages of design (e.g. optioneering).
- **Creating new means of engagement** between regulator and relevant stakeholders (both structured and less formal fora) could enable more effective communication and facilitate the licensing process of innovative solutions.
- **Lessons learnt** exercises involving regulators and licensees could provide a positive way to reflect on challenges and opportunities that emerge from licensing.
- The use of inactive **mock-ups (including digital twins) or active demonstrators**, or both, could provide a good opportunity to de-risk the final licensing of a full-scale plant involving innovative solutions.
- The implementation of a **robust defence in depth** can provide a positive means by which solutions imported from other less hazardous industries can be safely deployed in the nuclear sector, e.g. by placing a modest claim on the novel solution and consequently reducing the substantiation/licensing effort.
- **Upfront work on the safety case** can be carried out by considering safety in parallel with the design from early stages of development.
- **Realistic planning** of the implementation of a new technology with the timely involvement of key stakeholders could help target the efforts of various stakeholders.

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3. Benchmarking

3.1. Introduction

Much of the work in waste management and decommissioning is currently done by hand, which is associated with hazards for personnel. One crucial question that needs to be asked is: What steps does the nuclear sector need to take to initiate the transition towards a scenario where many of the operational risks to personnel are minimised or eliminated? Enhancing the use of robotics and remote systems could be one step; however, a primary challenge to accelerating the transition from manual labour to RRS in the field of nuclear decommissioning is proving the level of readiness and reliability of the robotic and remote systems available. Indeed, this information is required to support regulatory bodies, decision makers, programme managers and project leaders in their assessments and decision processes. To meet that challenge, the EGRRS has identified that one of the solutions is to build a benchmarking database hosting data to assess and verify the different robotic and remote systems independently.

The use of benchmarking is common within the nuclear industry and is regularly performed in other industries such as heavy industries, medical manufacturing, mining and sales. There are many benefits to be gained from benchmarking, among which:

- Increased efficiency
- Increased safety from knowledge gained on methods and systems proven in the field
- Better understanding of tasks and challenges from analysing and benchmarking against tasks
- Finding alternative or multiple solutions
- Applying better technologies to existing problems

However, applying traditional benchmarking approaches to the nuclear industry proves challenging due to the absence of a clear "market leader" and "reference cases" in this highly specialised field. Each country and site within the nuclear sector operates under distinct interpretations of international regulations, unique local cultures and faces diverse technical challenges. This inherent diversity renders the conventional benchmarking methodology impractical.

To overcome these challenges and tailor benchmarking to the nuclear domain, the proposed approach involves circumventing site-specific differences and focusing on the fundamental tasks associated with decommissioning and waste handling. By emphasising task-centric evaluations, it is possible to extract valuable insights and make meaningful comparisons that transcend the complexities arising from divergent regulations, cultures, and technical nuances across nuclear sites. This strategic shift allows for a more relevant and actionable benchmarking process within the unique landscape of the nuclear industry.

In recognition of the inherent susceptibility to bias in benchmarking processes, the EGRRS has taken a proactive stance by introducing an initiative aimed at enhancing transparency in benchmarking methodologies. The EGRRS has crafted and disseminated clear guidance on benchmarking practices and has collected both internal and external feedback, see Appendix 2. By adopting this approach, the EGRRS not only underscores its commitment to impartiality but also ensures that benchmarking within the realm of nuclear decommissioning is founded on robust, validated methodologies vetted by expert figures in the field.

3.2. Terminology

To clarify and to set a common ground for discussion, the following section aims to define some key concepts and tools:

- RRS (robotics and remote systems)
- Benchmarking
- Databases

3.2.1. Robotics and remote systems

Robotics and remote systems can be defined as systems or machines that are typically used to perform tasks instead of humans. The reasons that RRS are used can include efficiency, economics and safety.

The deployment of RRS in various industries, such as in manufacturing, in smelters, and for medical manufacturing, has greatly improved the capacity of those fields and increased safety for personnel.

When discussing RRS in the nuclear back-end, there are three main types of robotic systems.

- (Power) manipulator arms
- Mobile robots or systems
- Stationary robots or systems

Each option can come with different power options and is typically designed in various configurations that impact how the machine operates in a space. Some configurations are:

- Cartesian: The robot can move in straight lines, allowing for restricted movement.
- Cylindrical: The robot's arm can turn around and move up and down a central axis.
- Spherical: The robot moves around a primary axis, as well as a secondary one located at a 90° angle to the primary axis.
- Delta/parallel: This configuration enables faster movement for the robot, using sweeping motions to move outward quickly.
- Selective compliance articulated: This configuration has pivot points, allowing the robotic arm to move in Cartesian and cylindrical directions.
- Articulated: This configuration requires the robot to have a wrist and elbow joint, along with at least one shoulder joint.

The configuration of the RRS determines suitable tasks or areas of work. When performing decommissioning and waste handling activities, the capability of the RRS must be taken into account in the cost-benefit analysis of the investment of the RRS.

3.2.2. Benchmarking

Benchmarking is a process of measuring services, performances, and processes against one another or against known leaders in their respective operation/field. When performing benchmarking, the purpose of the output is to be able to clarify and visualise which of the benchmarked items, systems, company, etc. meet the right criteria for that specific application.

When discussing benchmarking within the nuclear back-end, it is hard to use a benchmarking standard as each site is in some ways unique and each has its own special prerequisites and limitations. On the other hand, many of the tasks that will need to be performed when handling and packaging nuclear waste or performing dismantling activities are very similar or identical.

Therefore, benchmarking in the nuclear back-end is often not carried out for the regulators, programmes and projects that need to plan work activities.

3.2.3. Databases

Databases are sources of information and can typically be described as relational or non-relational. A relational database stores data in tabular form (columns and rows) and is often considered structured data.

Non-relational databases extend the capabilities of a database by allowing data to be stored in non-tabular formats, which makes them more flexible. Data are stored in key-value pairs, where each key defines an associated dataset, which can include values, lists/vectors, text and images.

These methods are a pure database form and require hosting and a query tool. A relational database could be nothing more than an excel workbook shared online. If the data are hosted on a server, a query tool would need to be available to allow the user to access and search the information.

3.3. The limitations of current benchmarking approaches

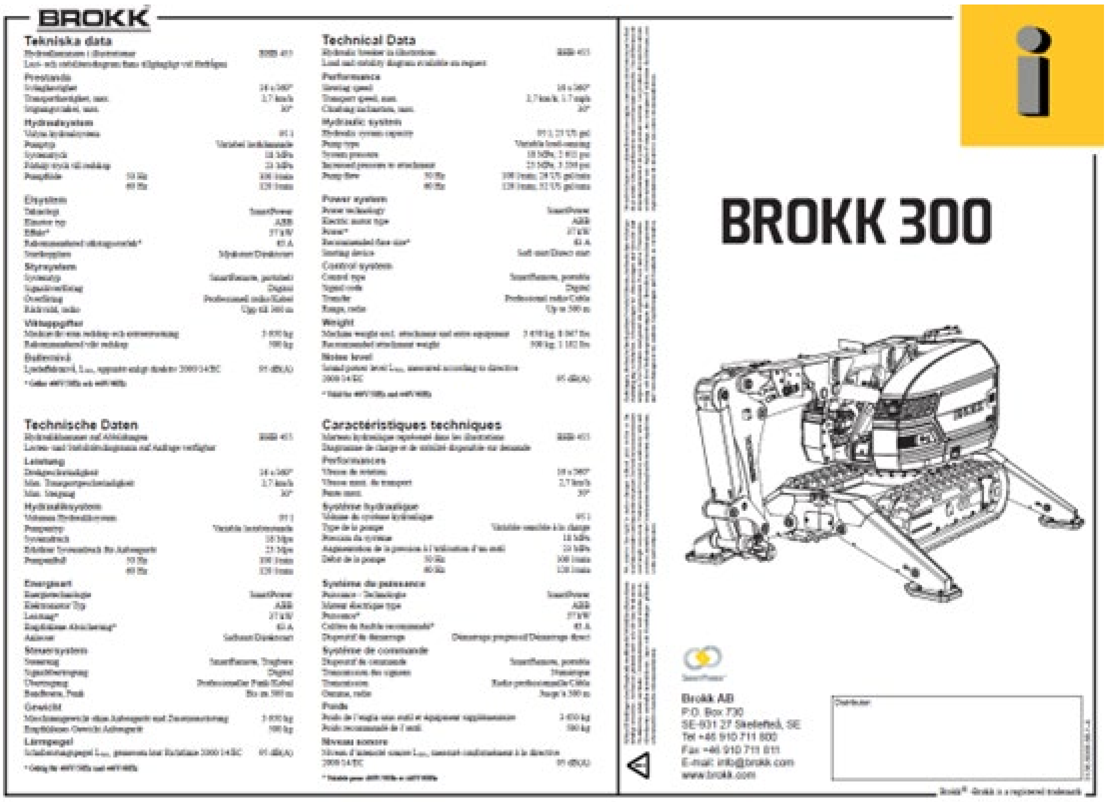
3.3.1. Typical approaches to benchmarking of RRS in the back-end

Usually, two approaches are used to describe a remote-controlled system:

1. **Technology-based approach**: One common approach, when describing a robot, is to provide a comprehensive overview of its capabilities. Descriptions of robots or remote arms revolve around factors such as load capacities, the number of mobility axes, and reach length. Absolute precision and repeatability are also commonly highlighted, while obtaining information on capabilities related to resistance against vibration, heat and, more significantly, maintainability in challenging environments is often more difficult. Manufacturers usually attach a datasheet that describes some of the technical data of that system/robot; see an example in Figure 2. However, this is often done in isolation from its intended application within the specific context of nuclear constraints, and without considering the expectations of the end users. These descriptions tend to compare the robot's capabilities with benchmarks from other industries, even when the operational context differs significantly, such as comparing underwater usage to closed, ventilated areas, or irradiated to non-irradiated environments. Furthermore, critical parameters can vary greatly. For example, precision and repeatability are vital in the manufacturing industry, whereas safety, reliability and emergency rescue under high dose rate environments take precedence in nuclear applications. Maintenance

and emergency rescue are much more important drivers in the decision-making process as even trivial maintenance operations can become painstakingly complex and thus expensive in the nuclear sector.

Figure 3.1. Technical Brochure for the BROKK 300



2. **Project-based approach**: In another approach, attention is directed towards specific projects, often after their completion. In these cases, the emphasis is, most of the times, placed on highlighting the achievements and success stories rather than describing in detail the challenges faced during the project execution. Consequently, it becomes challenging to validate the relevance of these successes for other projects. Occasionally, these projects consider the weaknesses of the robotic system from the start and make adjustments to scenarios, incorporating factors like maintenance and other considerations already early in the design decisions.

These two approaches, while efficient in other fields, are not fully addressing the needs of the professionals in the nuclear back-end, as there are specific challenges that need to be taken into account.

3.3.2. Some specific challenges found in the nuclear back-end

In the realm of benchmarking, the assessment of general robotic solutions often takes place within the context of a typical industrial environment. However, when dealing with the nuclear industry and back-end sites, a host of critical constraints come into play, altering the analysis. These constraints include factors like radiation dose impact, contamination risks, maintainability challenges, and the specialised skills required for nuclear operations.

Availability of specialised skills

In conventional industrial settings, robots are commonplace and are managed by dedicated teams with specific expertise and ongoing supplier relationships. However, in the nuclear back-end, staff typically possess more basic mechanical or electrical skills and it is challenging to retain specialised resources due to sporadic robot use. Manufacturers are often reluctant to invest in dedicated support teams due to the small volume of nuclear applications and the effort for documentation required in the nuclear field.

Constrained environments

To illustrate this point, consider a scenario where hot cutting is sanctioned during the project's initial design and safety case phases, contingent upon specified ventilation parameters. In the course of the project, these ventilation targets become unattainable due to the actual conditions of the ageing plant. Consequently, a robotic system designed for an 80% plasma cutting and 20% disc cutting balance is forced to exclusively perform disc cutting, leading to heightened maintenance needs, increased operator radiation exposure, delays and, ultimately, elevated project costs. This example highlights the complexity of evaluating robotic solutions solely on their intrinsic capabilities. Instead, a holistic assessment from an end-user perspective is imperative, incorporating the unique contextual factors of the site and adherence to nuclear safety requirements. While ongoing research and development can certainly enhance robotic performance, strategic decision making regarding technology choices in the early project stages proves to be more advantageous in scenarios constrained by time and budget. It underscores the necessity for a nuanced understanding of the broader operational landscape and safety implications, ensuring that the chosen robotics align seamlessly with the intricacies of the project environment.

Another key element to consider when looking at the nuclear back-end is the accessibility of the RRS. In a standard industrial environment, access to a robot is typically straightforward and direct. Workers can easily interact with the equipment in an adapted area without significant hindrances. In contrast, within the nuclear back-end, access to equipment can be an arduous challenge in itself. Retrieving equipment from inaccessible areas can be a lengthy and costly endeavour, and even after extraction, the equipment often remains contaminated and necessitates decontamination of accessible parts. Notably, not all parts are easily accessible.

Maintenance tasks within this constrained nuclear environment further introduce unique challenges, especially for the personnel involved. Maintenance activities may require personnel to wear protective suits and extensive personal protective equipment (PPE). Furthermore, damaged parts are often contaminated and cannot be sent back to the manufacturer for analysis, while on-site visits from manufacturers are often not feasible. In this complex nuclear context, even seemingly routine maintenance actions become intricate, protracted and subject to uncertainties. These distinctive challenges underscore the need for specialised solutions and a tailored benchmarking approach that accounts for the unique constraints of the nuclear industry.

Extended periods of time

Additionally, the nuclear industry's prolonged design and approval processes contrast with the rapid technological obsolescence of robots, particularly in decommissioning and waste management projects, which can span over decades. Tests and modifications over several years may become outdated, making spare part procurement difficult and requiring interface adjustments. During this protracted time frame, conventional technologies may undergo significant transformations, rendering the chosen robotic solutions partly obsolete by the time they are deployed in the field. Adding a layer of complexity, key personnel involved in the initial design may no longer be associated with the project due to factors such as retirement, turnover or promotion. Consequently, any comprehensive assessment must consider the maturity of the technology, potential obsolescence processes in context of the extended timeline of a nuclear project, and the imperative role of documentation and knowledge management over the years, which becomes a crucial element in the project's risk management portfolio

Moreover, from the end-user perspective, meticulous cost management emerges as a pivotal concern. The aforementioned examples underscore that cost estimation should not be limited to the upfront investment; rather, it should encompass operation and maintenance costs. Given the extended duration of these projects, coupled with the inherent uncertainty in initial data, evaluating solutions based on their accessibility to non-experts and adaptability are of the utmost importance. It is imperative to acknowledge that these considerations play a pivotal role in achieving project targets within the stipulated time frame and budget, while also accounting for plant intricacies, safety standards and unforeseen constraints.

3.3.3. A benchmarking approach focusing on the end user

While the literature is full of success stories and technical aspects of robotics solutions, these narratives often lack practical value for end users grappling with nuanced decision making (NEA, 2011; PNNL, 1999; European Commission, 1998). Existing benchmarking initiatives, albeit valuable in their own right, have primarily focused on diverse perspectives such as regulatory and overall performance. However, after a thorough examination of the limited number of available databases, an absence of end-user considerations becomes apparent.

The EGRRS identified data limitations including:

- Lack of real information regarding the maturity of the solution.
- Absence of application lessons learnt, particularly with specific issues.
- No provision for long-term reviews to enrich the benchmark over time.

In response to this gap, the EGRRS advocates for a comprehensive approach that incorporates both end-user perspectives and a focus on tasks specific to the nuclear industry context, thereby offering a more holistic and pragmatic benchmarking framework.

To address the inherent complexity of RRS applications in the nuclear field, the EGRRS benchmarking database proposes to adopt a task-oriented approach. The strategy is to navigate the intricacies of regulatory variations by zeroing in on tasks that are comparable across countries and sites. From a technical standpoint, the execution of a task, such as cutting a pipe, remains consistent, regardless of the site or country. It is important to recognise that the broader context may introduce variations in the effort required for the same task at different sites and in different countries.

In essence, the members of the nuclear industry acknowledge that there is no universal solution applicable to all challenges across diverse sites and countries. Instead, they recognise the need for a nuanced and sophisticated approach to match the right tool with the specific circumstances at hand. The EGRRS benchmarking database is conceived to serve as a valuable resource in this regard, offering the nuclear community a platform to navigate the complexities and find optimal solutions tailored to their unique challenges.

3.4. Other initiatives

The growing amount of online information available on RRS from technical, marketing or academic sources enables the development of digital tools to sort and characterise with a systematic approach innovations and new solutions proposed to the market. At the national and international levels, the initiatives described below aimed at providing structured guidance based on media tools to end-user or stakeholders.

When looking into other databases available in the nuclear back-end, it becomes obvious that there are few options available, with the majority focusing on national experiences and lessons learnt such as the GRS Wiki for Germany and NETIS in Japan. Additionally, the IAEA IDN Wiki is available for member states and other organisations. The following section introduces some of these initiatives.

3.4.1. YCB Benchmarks

In 2022, the EGRRS invited external experts in the field of robotics who had developed benchmarking practices. In particular, Berk Calli presented the YCB Benchmarks. A summary of his presentation and the following discussions can be found in Appendix 2, section A.2.

3.4.2. MediaWiki

Wikipedia is built on the software MediaWiki. It is open-source software that enables users to collect and organise knowledge and make it available to others. "The wiki way" is to make bad changes easy to fix rather than hard to make (i.e. errors can be quickly identified and corrected by the user community rather than a set of approved editors). MediaWiki processes and displays data stored in databases and writes the edits made by users to the databases without deleting previous page versions. Therefore, there is the ability to have version control of edits. MediaWiki is designed for open content and may not be suitable for instances where parts of the content are restricted. It can be hosted on internal networks where only approved individuals can see the information. It is also complex to set up and maintain, and documentation is a work in progress supported by volunteers. MediaWiki could be used for the EGRRS database.

3.4.3. The GRS Wiki and its lessons learnt

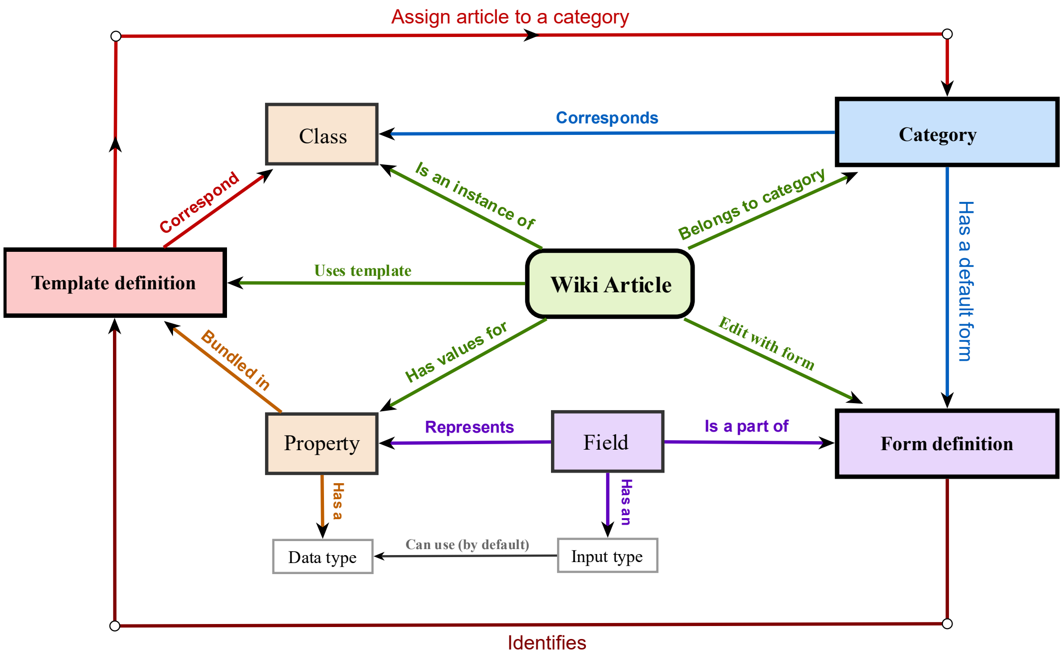
The GRS has been using a semantic wiki for the internal knowledge management for several years. The Wiki focuses on the decommissioning of nuclear facilities in Germany. Besides the power reactors, this covers research reactors as well as other facilities of the nuclear fuel cycle.

In the first instance, the GRS Wiki was seen as a testbed to develop a new system for knowledge management and preservation. For this purpose, a first version was already installed on the company's own servers in 2017, which was used only by a small internal group of people. In terms of content, this wiki was also limited to a few topics and content.

Already in 2019, a first major upgrade took place, which was accompanied by a complete reinstallation of the software and a migration of the data. From this point on, significant technical changes within MediaWiki were carried out by GRS itself.

In this context, however, it was necessary to understand the functionality of the MediaWiki and its extensions much more profoundly than it was necessary for the pure editing of information. Up to this point, editing by GRS was limited to texts and content in individual articles, pages, shown in green in the centre of Figure 3. All further, necessary adaptations in the other areas of the installation, i.e. the definition of classes and attributes, the creation of templates and forms as well as the redesign of already existing structures had to be learnt piece by piece and adapted and improved continuously over the course of two years. But also changes outside the installation environment, i.e. in the configuration of MediaWiki itself, were necessary to achieve the desired results.

Figure 3.2. Data model and handling of a semantic Mediawiki



Source: Julien Da Costa and Daniel K. Schneider, CC BY-SA 4.0, via Wikimedia Commons.

Having an external service provider for the implementation of the desired adjustments did not prove to be expedient. On the one hand, there were misunderstandings about the exact implementation of input and output options, links, and functions. On the other hand, there were sometimes long delays in the implementation. As a result, work on the wiki and its contents was delayed and content had to be re-entered.

For this purpose, the extension Page Forms was used to design forms. The forms fulfil several tasks. On the one hand, GRS accepts the information entered and forwards it to the stored templates (see Figure 3). On the other hand, GRS makes it possible to ensure a consistent structure in all articles that are edited with the same form. The form has different areas for this and can be designed with text fields, text areas, date fields, control fields and selection fields, among others. The information entered can be directly semantically annotated by the stored templates and made accessible to the system. For the power reactor form alone, the number of annotated fields has been increased from about 25 to over 150. Of course, an environment less heavily based on numbers and data can get by with far fewer attributes.

After the successful collection of a larger amount of data and information, the circle of users within GRS was expanded. However, this also increased the complexity and diversity of the data and information. Further adjustments and additions were necessary.

Another aspect to be considered in the use and further development of a MediaWiki system is that it is not aimed at programmers. Hence, it should be able to be edited with little knowledge and simple means. This circumstance is initially, and for the use by a wide group of users, very advantageous, but in the further development it leads to difficulties in many places. In MediaWiki, all information entered by users, whether with a form or directly on the page in the Wiki source code, is stored directly on this page. This is advantageous, because the user does not have to deal with a database. However, disadvantages arise when querying semantically annotated data, as this must now be queried from all pages on which it is stored.

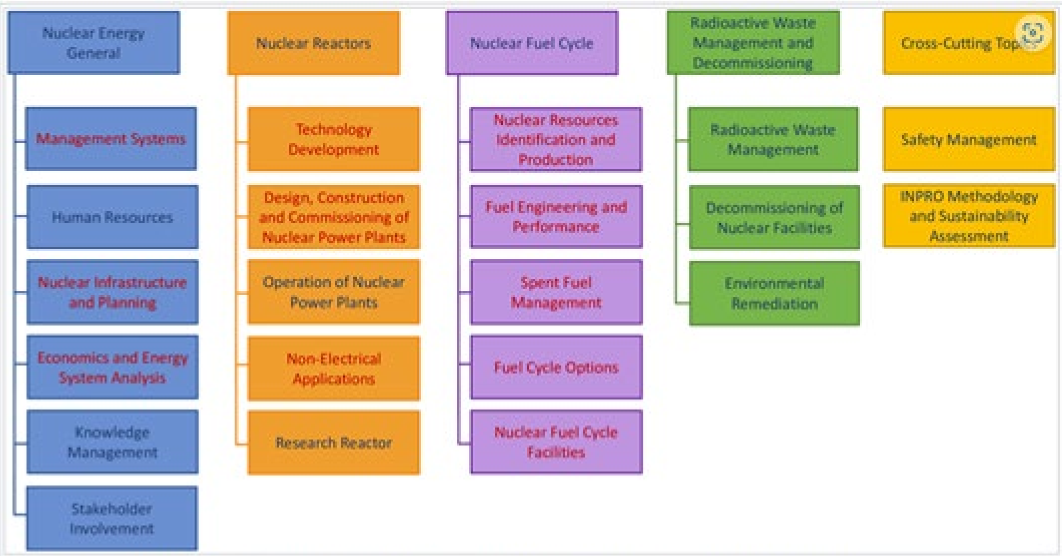
Therefore, from the EGRRS perspective, the wiki does not replace a database for documents but rather adds a new layer to them. Information can then be linked to this new layer, which increases its visibility.

The GRS database presents accessibility challenges for individuals beyond the German nuclear sector. The EGRRS objective is to establish a platform that is readily accessible to professionals in the nuclear sector worldwide, without regard to their geographic location or the specific country in which they are situated. This commitment to enhanced accessibility aligns with the NEA´s vision to create a resource that transcends borders, fostering collaboration and knowledge-sharing on a global scale within the nuclear industry.

3.4.4. Information on the IAEA IDN wiki

The International Decommissioning Network (IDN) maintains some parts of the IAEA Nuclear wiki. This wiki is based on MediaWiki software, like the GRS database. Figure 3.3 shows the structure of the database.

Figure 3.3. Topical overview of the IAEA Nuclear wiki



Topical overview of IAEA Nuclear Wiki. Please note that a red link, signifies that the topical area pages have not yet been developed.

As shown on: https://nucleus.iaea.org/sites/connect/IDNpublic/SitePages/Nuclear-Wiki.aspx

The IAEA Nuclear wiki shares similar goals to the EGRRS in that it aims at enhancing co-operation worldwide and to serve as a reference. As stated in their wiki introduction, the userbase comprise relevant stakeholders:

- Site licence holders
- Waste management organisations

- Supervisory authorities (ministries, regulators, environmental authorities, etc.) and their technical support organisations
- Universities and research organisations
- Supply chain companies

Figure 3.4 below shows a typical entry page.

Figure 3.4. Screenshot from IAEA Decontamination and Dismantling Technologies wiki page

Note: taken in December 2023

Source: https://nuclear-wiki.iaea.org/wiki/Decontamination_and_dismantling_technologies.

Upon analysis of the IDN wiki, it is evident that it lacks clear and straightforward guidance on the various methods, systems, and techniques available for performing different tasks in the nuclear back-end. Furthermore, there is a notable absence of evaluations on different methods within the IDN wiki. While some wiki entries present simpler case studies, these vary significantly in the quantity of data and the level of information that can be extracted from them.

In summary, the existing landscape lacks an easily accessible and comprehensive database that aligns with the objectives set for the benchmarking and database initiative within the EGRRS. The intention is to fill this void by creating a resource that not only provides clear guidance but also offers robust evaluations of different methods, systems and techniques employed in the nuclear back-end.

3.4.5. Technology transfer and lessons learnt assessment by EPRI

Since its creation in 1972, EPRI has supported expert collaboration between more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable and equitable access to electricity across the globe. As part of its mission as an independent, non-profit energy research and development organisation, several activities to support technology transfer as well as support collecting lessons learnt have been carried out.

In the area of robotics, several initiatives have been implemented for different applications. Pertinent to collected information in decommissioning and radiological protection, the following reports have been made available for public access:

- Evaluation of System Automation and Robotics for Decommissioning Applications (3002010599)

- Application of Non-Nuclear Robotics to Nuclear Industry Decommissioning (1009571)
- Robotic Process Automation for Nuclear Power Plants: Evaluation of Near-Term Opportunities (3002023899)
- Design and Demonstration of an Autonomous System for Radiological Characterization of Building Surfaces (3002023966)
- Design and Demonstration of an Autonomous System for Radiological Characterization (3002018420)
- Autonomous Indoor Radiation Survey and Inspection Drone Demonstration at Peach Bottom (3002018409)
- NextGen RP – Specifications for Autonomous Contamination Survey Robots: Functional Specifications Document (3002023839)

With the growing interest and capabilities in robotic systems (in particular with mature drones and quadrupeds) EPRI has sponsored an industry working group in the area of radiological protection. Through the collaboration of utility members, robot manufacturers, and companies that sell and distribute radiological protection handheld and advanced instrumentation, best practices for the implementation of robotics specifically for radiological protection related tasks and use cases were collected and provided in EPRI report 3002028838 "Robotics for Radiation Protection Tasks: Implementation Guide." Some of the findings include:

- *Challenges:* Robots are expensive and have been damaged, contaminated, destroyed, and become stuck. They can be difficult to implement programmatically (e.g. security, IT, physical restrictions, culture) and they cannot navigate the plant fully autonomously in many cases.
- *Benefits:* Keeping people out of harm's way, reduced dose to personnel, preventing outages or down powers, better characterisation and trending of radiological data, freeing up radiological protection technician's time for other tasks
- *Gaps:* Taking smears, software for radiological change detection, software for integration with existing survey record systems, improved cooling, improved geofencing to avoid areas, remote activation of doors and elevators
- *Major take aways:* Ownership of a robotics programme is crucial, cybersecurity is a major challenge, most tasks cannot be done completely autonomously, use cases/value tend to grow after purchase

As introduced in section 2.2, cybersecurity concerns are often faced by the robotics programme team early in the creation of their programme or implementation of new hardware. Since robotic systems may present unique avenues of exploitation, they often need specific consideration prior to implementation.

With the growing maturity of data science and machine learning, EPRI is engaged in analysing and verifying the opportunities of these state-of-the-art technologies (natural language processing techniques and large language models) to support smart information retrieval systems (including semantic, lexical searches and knowledge graphs).

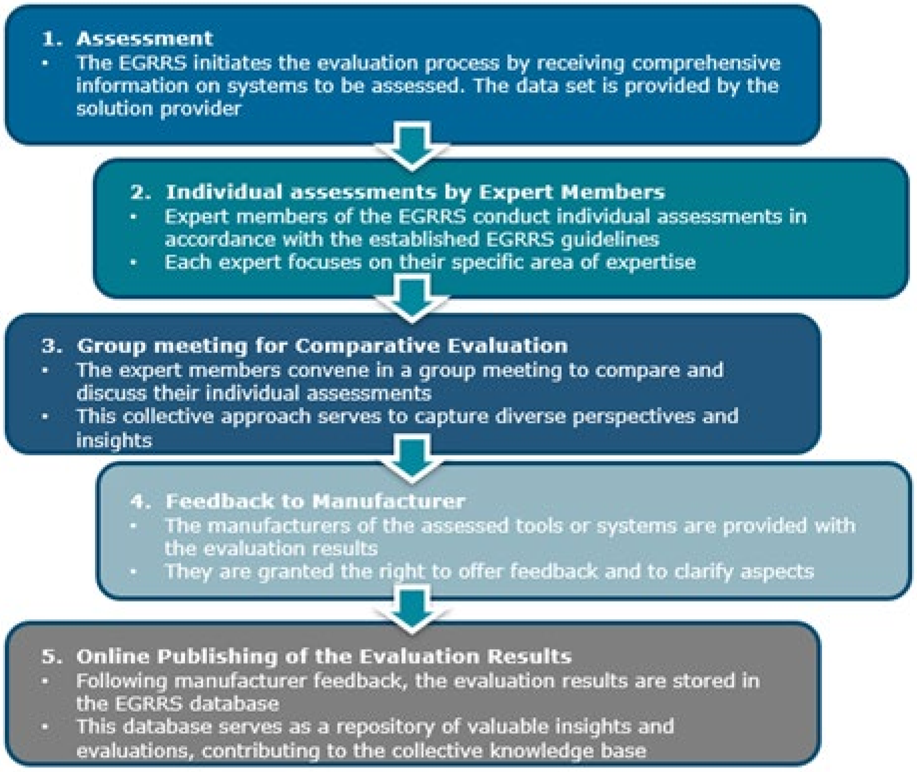
3.5. The EGRRS approach to benchmarking

The overarching objective of the EGRRS is to engage in the benchmarking of both existing and emerging, newly developed robotic systems, remote technologies, and associated innovations within the nuclear sector. The intention is to categorise these technologies within a comprehensive database, designed to serve as a valuable resource during the planning and execution phases of robotics integration in the nuclear back-end. This initiative seeks to provide stakeholders with a robust support system, to guide informed decision-making processes, enabling the selection of optimal RRS technologies that can seamlessly integrate into day-to-day business operations. This strategic approach is anticipated to contribute to a global reduction in costs associated with RRS implementation and concurrently mitigate risk exposures for operators.

By having a straightforward task-oriented database, the boundaries for systems to be tested is clarified for both the manufacturer and regulator. This database is designed to be easily accessible to a diverse range of stakeholders, including clients, operators and regulatory bodies. By adopting this approach, the EGRRS endeavours to contribute to a standardised and effective evaluation of RRS technologies within the nuclear domain.

The input flow to the database is found in Figure 3.5, and described in further detail below.

Figure 3.5. Proposed input flow to the database



3.5.1. Conceptual methodology and input flow to the database

Assessment:

The EGRRS initiates the evaluation process by receiving comprehensive information on systems to be assessed. The data set is provided by the solution provider.

Group evaluation

Individual assessments by expert members**:** Expert members of the EGRRS conduct individual assessments in accordance with the established EGRRS guidelines. Each expert focuses on their specific area of expertise, ensuring a thorough and specialised evaluation.

Group meeting for comparative evaluation: The expert members convene in a group meeting to compare and discuss their individual assessments, therefore ensuring a comprehensive evaluation. This collective approach serves to capture diverse perspectives and insights.

Feedback to manufacturers: The manufacturers of the assessed tools or systems are provided with the evaluation results. They are granted the right to offer feedback and to clarify aspects. Their reply can be integrated in the assessment

Accessibility of the results

Online publication of evaluation results: Following manufacturer feedback, the evaluation results are stored in the EGRRS database. This database serves as a repository of valuable insights and evaluations, contributing to the collective knowledge base. This transparent dissemination ensures accessibility to stakeholders and facilitates an informed decision-making process.

Ongoing database enrichment and review: Over time, the EGRRS actively enriches the database, incorporating new benchmarks and updates. The database undergoes regular reviews to align with emerging technologies and industry advancements. Solutions that remain unused may be reevaluated or removed, maintaining the relevance and accuracy of the benchmarking data over the years.

3.5.2. Impartiality

To ensure the evaluation group's independency, experience and expertise, and that the assessments will be of benefit to all parties involved, the EGRRS should in the coming years work towards organising such an assessment group within the EGRRS.

The EGRRS will build on the NEA experience on setting up international peer-review, such as been done in the past by the Radioactive Waste Management Committee (NEA, 2005, 2014).

3.6. Categorisation of the tasks and systems

To take a sustainable approach on the benchmarking, some focus in the proposed database is to ensure that the systems/robots are being evaluated against a wide variety of tasks to ensure multiple areas of use – and in the long run, making less of an environmental impact for robotic implementation.

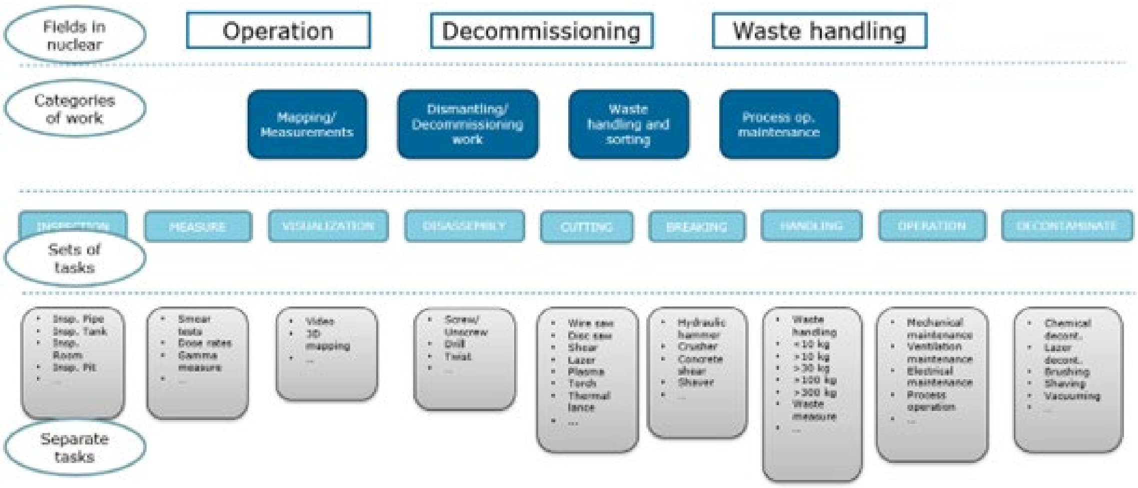
Working on the task to be performed will include assessment of the global ability to perform some tasks in a specific environment, and not only the maturity of the various elements of the solution. For example, some off-the-shelf arms designed to be used for thermal cutting operations under water are provenly operational in those condition but may not be mature enough to perform disc cutting in air in a confined area. The proposed assessment process will take in account the ability to deliver and not only its theoretical potential.

By initially categorising the systems into different fields within the nuclear industry, followed by segmentation into specific categories, fields of tasks, and ultimately individual tasks, the identification of opportunities for system utilisation throughout the entire nuclear life cycle becomes more straightforward.

In order to make an impact and start drafting the outlines of the database, the EGRRS analysed the various tasks and works that could be performed by robots or remote systems and found four "main" categories (see Figure 3.6):

- Mapping/measurement and investigation – to monitor or measure radiation of various kinds to allow a better understanding of the physical conditions of the plant
- Decommissioning works – dismantling or decommissioning activities
- Waste handling – separating and packing waste and other subtasks in the field
- Revision/Service – tasks that are within the maintenance field

Figure 3.6. Categories of tasks that can be performed by RRS in the nuclear back-end



Within each overarching category, there will be further delineation into subcategories, each serving to define distinct types of work. Subsequently, within these subcategories, different sets of tasks will be identified. The ultimate objective is to provide clarity to the end user, such as a regulator or project manager, regarding the specific nature of tasks to be undertaken. Users will have the capability to conduct targeted searches across various tasks within different fields, thereby receiving tailored suggestions on suitable robots, remote systems and other technologies. These recommendations will be based on thorough evaluations and proven track records within specific tasks, ensuring a streamlined and informed decision-making process for end users.

By pursuing this approach in the mapping task, the user encounters sets of tasks that are more straightforward to define. This facilitates the establishment of a benchmarking process that impartially compares various systems, leading to a more comprehensive understanding of the database landscape.

3.7. Examples of application of the benchmarking approach

The proposed categorisation can be used to perform a functional description of a system, as can be shown in Table 3.1 for a theoretical system. This functional description table will be adapted as the EGRRS collects more end user input.

Table 3.1. Functional description of systems to be benchmarked in the prototype database

Functional Description							
Operation/Field in Nuclear							
Operation of plant - O		Decommissioning - D		Waste Management - W			
no		yes		yes			
Categories of work							
Mapping/ Measurements -M		Dismantling/ Decom work -D		Waste Handling & sorting -W		Process Op. maintenance - S	
yes		yes		yes		yes	
tasks							
INVESTIGATE	yes	**CUT**	yes	**HANDLE**	yes	**DECONTAMINATE**	yes
investigation in pipe	no	wire saw	yes	waste handling <10kg	yes	chemical decon	yes
investigation in tank	yes	disc cutting	yes	waste handling > 10kg	yes	lazer decon.	yes
investigation in rooms	yes	shear cutting	yes	waste handling >30kg	yes	Brushing	yes
investigation in pit	yes	lazer cutting	yes	waste handling>100kg	yes	shaving	yes
MEASURE	yes	plasma cutting	yes	waste handling >300kg	yes	Vaccuming	yes
rad measure dose	yes	Torch cutting	yes	waste handling >300kg	yes	**OTHERS**	no
rad measure swiping	yes	Thermal lance	yes	waste masurement	yes		no
SEE	yes	**BREAK**	yes	**OPERATE**	yes		no
video/ camera	yes	Hydraulic Hammer	yes	mecanical maintenance	yes		no
DISASSEMBLE	yes	Crusher	yes	ventilation maintenance	yes		no
screw/unscrew	yes	concrete shear	yes	electrical maintenance	yes		no
Drill	yes	Shaver	yes	process operation	yes		no

As shown in the examples below, Figure 3.7 and Figure 3.8, any supplier or solution provider seeking an assessment of its equipment is required to complete the form. The form serves as a means for the supplier to furnish evidence of tasks performed using its equipment.

Figure 3.7. Form filled by Wälischmiller Engineering for a robotic arm

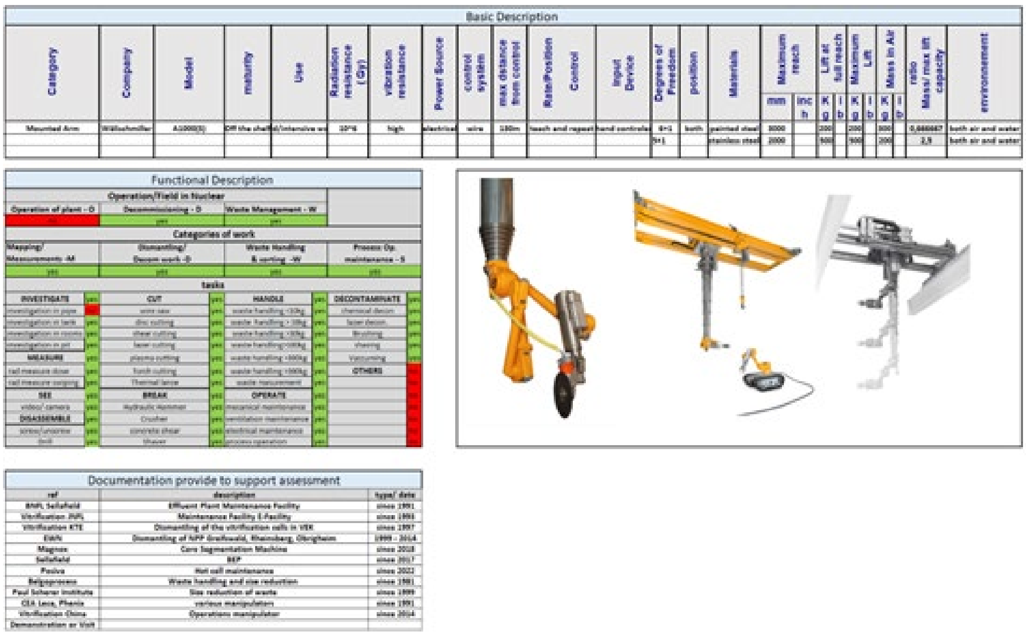
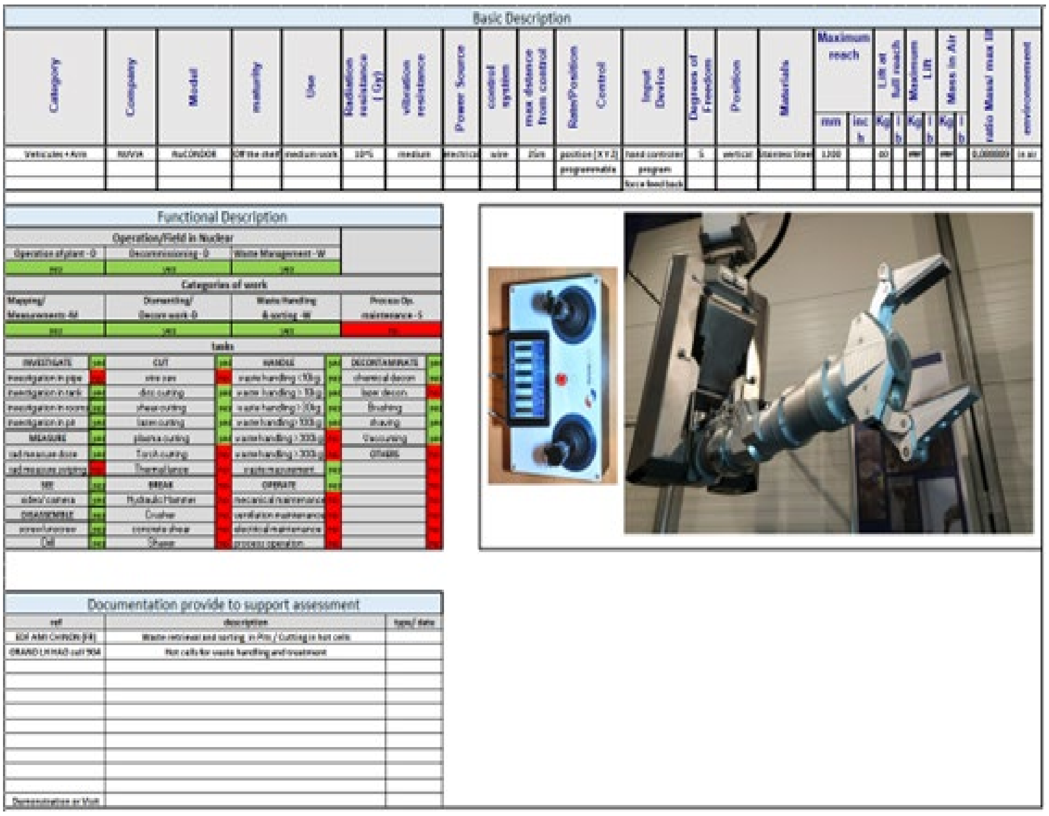


Figure 3.8. Form filled by Nuvia Technology for a robotic arm



As demonstrated in the examples, the assessment of each system will rely on a multitude of tasks proposed by the supplier, showcasing the range of capabilities that the robot can potentially execute.

3.8. Assessment methodology

In order to get a holistic, fair and qualified assessment, the EGRRS suggests that an independent assessment group consisting of known professionals from the NEA, IAEA and other non-affiliated organisations constitute the main part of such a group in order to guarantee its independence.

That group will have the mandate to build and refine the assessment methodology, the foundational principles of which are described below.

The primary concept is to simplify and categorise to enhance accessibility in the database/results, avoiding unnecessary detail. Focusing on minor differences between systems/robots could render benchmarking impractical. The aim is to facilitate effective comparisons across a broader spectrum, evaluating different systems with distinct strengths and weaknesses. The methodology allows for comments on each solution, offering precision on the solution's strengths or weaknesses (e.g. suitable for laser cutting but less precise for plasma cutting).

The EGRRS established a set of rules for assessing the maturity of solutions, distinguishing between those with proven experience and those with potential. An example of this assessment involves the expert group assigning ratings for each task based on the evidence and documentation provided by the applicant. This rating system is depicted in a simplified quotation table, see Table 3.2.

The quotation system allows for flexibility, accommodating emergent technologies and solutions rated between 1 and 3. It also supports ongoing development tracking through regular reviews. For instance, if a solution initially rated 1 improves to 2 within 6 months and then to 3 in another year, the community could anticipate active development and may consider it for feasibility studies. Conversely, if a solution rated 2 remains at 2 over time, it suggests limited suitability for the short-term future.

Furthermore, this approach provides a clear and task-specific view of the maturity level of each solution. When viewed collectively, it offers insights into the specialisation or generic capabilities of a solution, aiding in decision making within the nuclear industry.

Table 3.2. Quotation system

Quotation	Definition
NA:	not applicable
0	not possible
1	theoritical possible never tested
2	designed and tested
3	demonstrated on a representative mock-up
4	already used ponctually on a real project
5	extensively used with success, lessons learnt available

Table 3.3 shows how the quotation would be applied to a theoretical RRS.

Table 3.3. Example of a filled assessment form with quotation, applied to a theoretical RRS

Functional Description							
Operation/Field in Nuclear							
Operation of plant - O		**Decommissioning - D**		**Waste Management - W**			
no		yes		yes			
Categories of work							
Mapping/ Measurements -M		**Dismantling/ Decom work -D**		**Waste Handling & sorting -W**		**Process Op. maintenance - S**	
no		no		no		no	
tasks							
INSPECTION		**CUT**		**HANDLE**		**DECONTAMINATE**	
inspection in pipe	1	wire saw	1	waste handling <10kg	5	chemical decon	1
inspection in tank	2	disc cutting	1	waste handling > 10kg	4	lazer decon.	1
inspection in rooms	3	shear cutting	1	waste handling >30kg	3	Brushing	1
inspection in pit	4	lazer cutting	1	waste handling>100kg	2	shaving	1
MEASURE		plasma cutting	1	waste handling <300kg	1	Vaccuming	1
rad measure dose	5	Torch cutting	1	waste handling >300kg	0	**OTHERS**	
rad measure swiping	1	Thermal lance	1	waste masurement	3		1
VISUALIZATION		**BREAK**		**OPERATE**			1
video/ camera	1	Hydraulic Hammer	1	mecanical maintenance	1		1
DISASSEMBLE		Crusher	1	ventilation maintenance	1		1
screw/unscrew	1	concrete shear	1	electrical maintenance	1		1
drill	1	Shaver	1	process operation	1		1

The assessment form can be completed by individual comments and precisions by each expert of the assessment group, see Table 3.4, to complete and give more nuance to the quotation and include their personal experience to precise their position. Similarly, the applicant comments could be included the same way as part of the right to reply.

Table 3.4. Example of comments table to add nuance to the quotation in the assessment

COMMENTS		
task	**appreciation**	**Expert/date**

While limited, the different examples illustrate the philosophy of a simple but live database.

The proposed solution undergoes assessment via this methodology, with results and technical data stored in a wiki software accessible to members and interested parties. The wiki presents standardised technical data, expert group evaluations and accompanying comments. Regular updates, particularly concerning maturity or design evolution, are part of the ongoing process. The expert group can also provide insights into areas of optimal utilisation.

This methodology has the potential to extend beyond decommissioning projects, encompassing fuel cycle and waste treatment plants, especially if Master Slave Manipulators are to be included in the analysis, broadening the scope beyond the EGRRS mandate, and attracting a wider audience.

3.9. Roadmap for the benchmarking initiative

The endeavour to collect data, construct a database, and commence the assessment of robots and remote systems is a substantial undertaking that necessitates careful planning. The preliminary roadmap is structured into three distinct stages:

1. Early phase/Setting the scope (ongoing):

   In this initial stage, the focus is on laying the groundwork for the project. This step includes activities such as defining the scope of the assessment, establishing categories for benchmarking, and formulating the guidelines and methodology. Key tasks involve setting the foundational elements that will guide the subsequent phases.

2. Development phase/Gathering data (next 2-3 years):

   Transitioning into the development phase, the primary objective is to gather comprehensive data for the database. This involves reaching out to solution providers, developing the standardised technical database, and initiating the assessment process based on the defined methodology. Emphasis is placed on meticulous data collection and the systematic organisation of information.

3. Testing phase/Beta phase (in 4 years):

   The testing phase, also referred to as the beta phase, marks the stage where the database and assessment methodology undergo preliminary testing. This involves assessing a select number of robots and remote systems as a demonstration of the methodology's effectiveness. Feedback from this phase is crucial for refining and enhancing the system before a full-scale implementation.

By dividing the roadmap into these three stages, the project will progress systematically, ensuring that each phase is executed with precision and thoroughness, ultimately leading to the successful establishment of a robust benchmarking initiative for robots and remote systems in the nuclear industry.

3.10. Conclusions

The EGRRS has identified several pressing questions that warrant consideration. These questions serve as critical points of reflection as the EGRRS navigates the path ahead:

- How to gauge industry interest in using RRS?
- How to spread the use of the database and how to make users contribute?
- What is needed for the upkeep of a prototype live database?
- Who will host the necessary infrastructure?
- Who will assess the methods?
- Who will handle the logistic of the reviews?
- What should be the primary focus of benchmarking—tasks that the systems can perform or general system descriptions?

- Should benchmarking prioritise systems designed for a single specialised task or those capable of multi-use functionality?

In order to maintain the relevance of the approach through time, several additional aspects should be addressed such as the reviewers panel, (legitimacy, mandate rules), the supporting infrastructure for the tool (host server, updates and maintenance), access rules (fee, restrictions, communications).

Regarding the **reviewers**, it is of key importance for the relevance of the proposed approach and its durability to ensure that the assessors have proven expertise in the field. Clear information on their ties with evaluated solutions should be provided. The mandate of the panellists should follow clear rules about designation and duration.

Regarding the supporting **infrastructure**, a sustainable host solution should be identified and the issues of related support services such as updates, maintenance or security, should be addressed.

Regarding the **access** to the tool, clear rules need to be established according to the targeted audience. Access fees and/or restrictions may be applied. Specific communication or information dissemination plan can be developed to advertise it.

Regarding **financing,** considerations include expenses for wiki base management, updates, travel, accommodations for formal meetings, and participation in demonstrations and technical forums. A proposal is made to explore the possibility of seeking donations from solution providers for assessments and from users for access to the wiki base.

An analysis can be performed to highlight the strengths, weaknesses, opportunities and threats (SWOT) to the EGRRS benchmarking database proposal.

Strengths

- The benchmarking method will be task-oriented to address the needs of the end-user and to transcend site-specific considerations and cultural and regulation differences.
- The assessment will be performed collegially, by experts in the field who represent all stakeholders and are government-appointed.
- The benchmarking method will benefit from previous NEA peer-review initiatives and from available guidelines.
- The benchmarking method will take into account and integrate pre-existing standards as part of the assessments.
- The benchmarking initiative will rely on and foster a sense of community within the industry. It will bring professionals together, enabling them to discuss challenges, share past experiences, and explore potential solutions in the realm of robotics and remote systems.
- The database will support an effective horizon scanning.

Weaknesses

- The benchmarking method will need to keep up with the development pace of RRS. The rapid technological advancements may challenge the adaptability of the benchmarking methodology over time and might require recurrent reassessment.

- The methodology will have to take into account the bias from experts and will sometimes rely on subjective judgements, potentially leading to variations in assessments.
- The quality of the benchmarking will rely on the accuracy and availability of data which is provided by the solution provider.
- The assessment and the database infrastructure, including maintenance, will bear a cost that will need to be financed.
- The ability to share all details will be challenged for copyright, safety or security reasons. This might require reducing data amounts or learnings, thus lowering the overall comparison potential. The assessment can only be performed if the experts are both willing and available, which might create a bottleneck considering the time investment required.

Opportunities

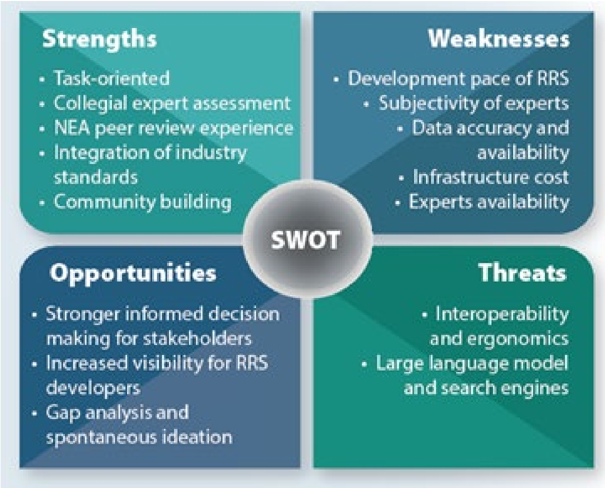
- The database populated with the assessment data will support stronger decision making for stakeholders, potentially saving time.
- By being featured in the database, the RRS developers might benefit from increased visibility, showcasing some of their solutions. This can also reduce transaction costs associated with information gathering and marketing.
- Population of the database might highlight missing applications and opportunities for technology combinations and development partnerships.

Threats

- The database will need to be user friendly to attract a strong user base, as well as to allow connection to other information portals with bigger user base (through Application Programming Interfaces). Lack of users might jeopardise the project.
- As large language models and search engines are opening new ways to manage knowledge, through unstructured data and beyond language boundaries, the benchmarking database will need to remain dynamic and to focus on the experts' assessments to remain relevant.

Figure 3.9 below summarises the analysis.

Figure 3.9. SWOT analysis diagram for the EGRRS benchmarking methodology



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4. Cost-benefit analysis

4.1. Cost-benefit analysis in the nuclear back-end

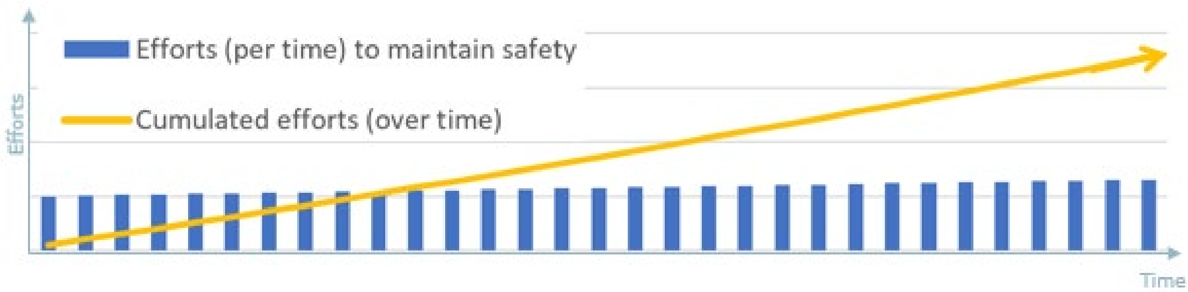
4.1.1. Benefits and efforts in the nuclear back-end

The nuclear back-end is typically characterised by the existence of:

- used contaminated facilities ;
- nuclear and/or radioactive inventory;
- management of post-accident site situations;
- risks implying efforts to maintain (control risks) or improve safety (eliminate risks).

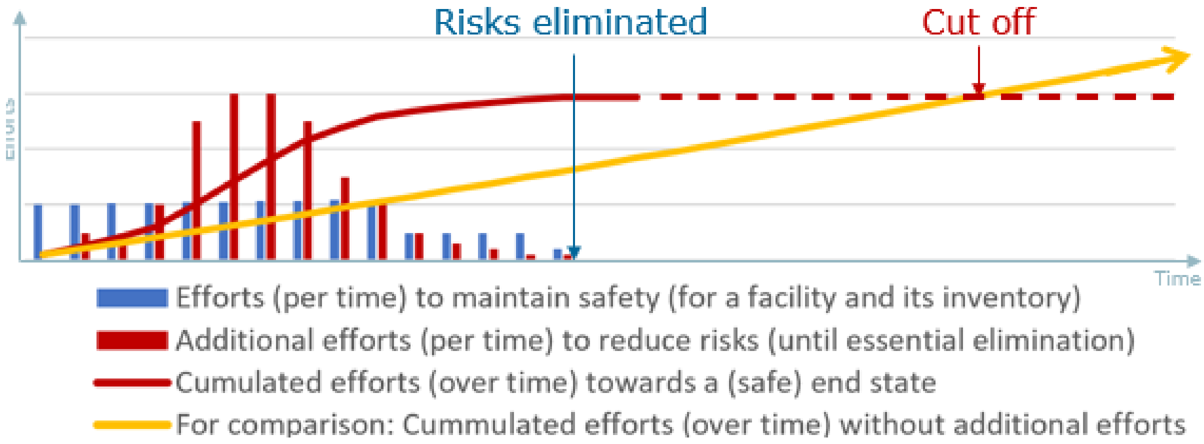
If there are no safety improvement measures or elimination of inventory and contamination, the necessary efforts to maintain safety will continue and the cumulated effort will grow forever, as shown in the following Figure 4.1.

Figure 4.1. Efforts to maintain safety on a back-end site over time



Thus, for nuclear back-end projects, the overall objective and benefit is the improvement of safety: the transformation of a facility and/or its inventory to a safer state – ultimately by achieving a safe end-state with the elimination of all essential safety risks associated with the facility and/or its inventory. Achieving a safe end-state will mean that all risks are essentially eliminated, and that no further efforts will be necessary. Accordingly, the efforts (risks) cumulated over time will stop growing, as shown in Figure 4.2.

Figure 4.2. Comparison of cumulated efforts when striving for safe end-state



A typical example would be the implementation of a nuclear facility decommissioning project with:

- removal of inventory in the facility;
- decontamination and dismantling of the facility;
- transfer of all radioactive wastes to a disposal site;
- release/clearance of materials from nuclear regulatory control;
- release/clearance of the site from regulatory control;

After this, all risks associated to the former nuclear facility are eliminated, which also eliminates any further efforts, such as for:

- maintaining an adequate workforce;
- inventory control;
- radiation control and protection (e.g. control of dose uptakes and radioactive releases);
- ageing management (e.g. for facility, for waste packages);
- management of secondary wastes;
- physical protection and site access;

This has the main (safety) benefits of:

- stopping further dose up takes;
- generating further (secondary) wastes; and
- eliminating risks of incidents and accidents.

From an economic point of view, the efforts taken can be translated into costs, and the main economic benefits would be primarily the value of generated safety, saved costs and the value generated by a site for reuse, if any.

In this sense, nuclear back-end projects differ from classical investment projects where the main targeted benefit is typically to generate profits by invested efforts.

4.1.2. Cost-benefit analysis for RRS in the nuclear back-end

A cost-benefit analysis (CBA) is a tool that is used to analyse and evaluate which method, system, or decision to make and which to forgo. The CBA sums the potential rewards, or benefits, expected from each action or decision, and summarises the total cost with taking that action or decision. The outcome of the analysis will determine whether the decision is financially feasible or if the decisionmaker should investigate another direction.

In the following, an approach for a cost-benefit analysis (CBA) adapted for nuclear back-end projects will be proposed, which may be used for supporting a decision related to the use of RRS.

As laid out in the previous introductory section, what separates the CBA in the nuclear back-end from the "standard" CBA is that the incentive is not to make profits, but in the end to ensure safety with optimised efforts.

In principle, when considering the whole life cycle of nuclear back-end projects, including the essential elimination of risks, it may be possible to calculate and compare the cost of all efforts, such as for radiological protection, waste management, incident, and accident mitigation, against the costs of continued efforts where risks are not reduced or eliminated. For comparison of expenditures at different times in the future, the net present value may be calculated and compared, and the alternative with the lowest costs would have a strong economic justification.

However, in reality, there are some challenges which are not easily resolved:

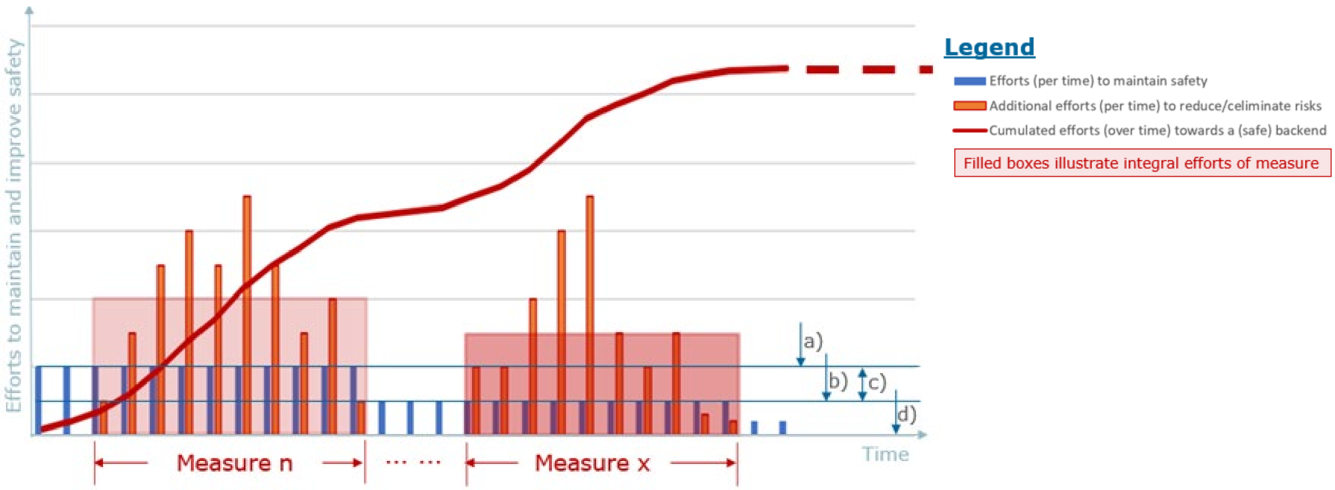
1. The nuclear back-end project normally consists of a series of measures which are typically configured for the next upcoming measures, in a context where details are missing and visibility on the future measures is limited, such that:
    - Only the costs of the current and maybe of the immediate next measures can be evaluated but not the total costs of the sum of all the measures.
    - The CBA is often expected to be performed for one or few single measures of a project and not the whole project.
    - The benefit (output) of one measure will typically not lead to the total risk elimination but parts of it.
    - The output will be risk reduction, which is difficult to value in cost.
    - The measure(s) may also be linked to risks, both impacting safety and costs, which may not be easy to evaluate.
2. If the final outcome is only risk reduction, it may become necessary to hold a difficult and often controversial discussion on assigning a monetary value to the targeted risk reduction beside the reduction of cost of future efforts: e.g. monetary value of dose reduction or inventory reduction, of reduced risk of incidences and accidents, of related perceptions of external stakeholders (authorities, politics) and of internal stakeholders (employees, shareholders).

Different approaches may be used to resolve the challenge. However, in the context of a technical choice or decision for a technical configuration, the challenge can be simplified through a comparative CBA.

The underlying concept of a comparative CBA described in the following is to focus on the achievement of a given output with a defined and fixed safety target (e.g. a targeted lower risk level) and to compare the safety and cost implications of different technical choices and configurations to reach the target. By assuming that for all the technical choices and configuration options the process to achieve the same output is justified by the same minimum requirements for safety (e.g. typically: dose uptake, waste generation, time and risks for implementation), it is not necessary to define a value for the risk level before and after the implementation the measure.

This concept would have the advantage that such comparative CBA could be applied for a single measure within a series of measures without interfering with the other measures. Figure 4.3 illustrates the concept:

Figure 4.3. Comparison of cumulative efforts



a. Necessary efforts to maintain safety due to risk level prior to "measure n"
b. Necessary efforts to maintain safety due to risk level after "measure n"
c. Reduction of efforts to maintain safety due to "measure n"
d. No further efforts necessary after essential elimination of risks after "measure x"

In Figure 4.3, the main safety benefit of the "measure n" is the reduced risk level (marked "b") after its implementation compared to the higher risk level (marked "a") prior to its implementation. The aggregated costs of the specific efforts (marked with red bars) taken in the measure will be the integral cost (marked with a red box) to implement the measure. In parallel to the implementation of the specific risk reduction measures the safety measures to manage the risks will continue until the risks will be reduced (from level marked "a" to the level marked "b"). With reduced risks the safety measures to manage them will be reduced.

Following this concept, the CBA may contribute to the justification and decision for application of RRS for implementing measures by identifying the better approach in terms of efforts invested to achieve the targeted safety benefit. In practice, the choice and the implementation of RRS primarily depends on the ability of the technology to minimise the efforts by improving safety, reducing time, reducing waste and/or reducing related risks to achieve the project results (benefits). Each of these aspects are associated with costs and a comparative analysis by difference building of costs of different options will provide an objective basis to substantiate a decision.

4.1.3. Possible safety benefits and cost impacts of efforts when using RRS

The benefits and costs of safety efforts need to be valued. The main elements of possible benefits and costs when using RRS are listed in the following tables:

Table 4.1. Possible benefits and related costs when considering the use of RRS

Topic	Possible safety benefit	Possible economic benefit/cost impact
Reduce or replace human intervention in dangerous environment	Reduced dose uptake.	Less qualified workers required for work in controlled zone required, Less limitation (and optimised) for work deployment control.
	Reduced needs for workers protection.	Less expenditures to related to workers protection required: training, PPE, clothes change, decontamination, …
	Reduced number of transfers between clean and contaminated zones.	Reduced needs for transfers with contamination control with eventual decontamination.
	Reduced secondary wastes generated.	e.g. limitation or reduction of used PPE, decontamination, …
	Reduce workers accident risk.	Less emergency preparedness and response needs.
Increase productivity for physical works and waste management (effectiveness and efficiency)	Reduced time for implementation, Lower probability for internal and external risk inducing events.	Reduced time for necessary maintenance of overall and specific security and safety infrastructure other than for RRS, (including also for emergency preparedness and response).
	More precise radioactive material segregation and sorting, Reduced waste volumes, Easier planning (e.g. simulation), operation (e.g. automation) and documentation (e.g. records) with information technology supported RRS.	Least cost management for materials and waste to be evacuated is supported: Maximise amount for free and restricted release of material, Minimising amount for higher radioactive waste categories.

As can be seen in Table 4.1, most of the possible safety benefits may also result in a cost reduction effect. What is not shown in Table 4.2 are the specific costs related to the choice and implementation of a safe RRS technology to perform the measure.

Table 4.2. Possible costs when using RRS

Topic	Security, safety and risk issues	Possible economic cost/cost for mitigation, management of risks
Choice and configuration of approach and RRS equipment	Misperceptions and errors due to lack of experience or reference cases.	Efforts/cost of studies, tests, R&D to close gaps, pilot project, competent staff building
	Uncertainties with regard of performance.	Efforts/cost of analysis of available documentation, tests, demonstrators, own tests and experiences, pilot projects, qualification of equipment.
	Unavailability or limited availability of equipment (including spare parts).	Efforts for market study, search of supplier alternatives, supplier chains. When procuring consider option to procure already additional reserve (e.g. additional unit, spare parts).
	Time and cost of procurement.	Number of suppliers may be limited, limiting competition impacting pricing and timely availability.
	Time and cost of installation and commissioning.	Efforts/cost for making a (presumably new and complex) RRS in a real specific context workable and productive.
	Reluctancy of stakeholders towards RRS as a new technology (e.g. own staff, regulator, shareholders, co-financers).	Additional efforts/costs to co-ordinate with stakeholders, mitigate eventual roadblocks, cost of delays, cost of modifying (or even cancelling) to pursue a specific RRS option during choice and configuration process

RRS Operation	Maintain security and safety during implementation:
	- Access control
	- Dose control
	- Zoning
	- Waste management
	- Emergency preparedness
	Safe implementation:
	- Works performed by RRS
	- Interventions to complement remote RRS works
	- Maintenance
	- Associated dose uptake
	- Associated waste generation
	- Emergency response
		Cost of:
		- Elapsing time during which security and safety of the site needs to be maintained
		- Qualified staff necessary for the RRS:
		  - RRS Operator Teams
		  - RRS Maintenance Teams
		  - RRS Intervention Teams
		  - Training/ qualification of the RRS staff (of above teams)
		- Investments
		- Energy and other consumables
		- Maintenance (spare parts, equipment)
		- Interventions (e.g. Radiation protection, preparation, trainings, precautions, PPE, supporting, equipment)

	Radioactive waste management: - Segregation, sorting, release of materials, - Type of primary and secondary radioactive wastes - Production of compliant waste packages	Cost of: - Waste management equipment procurement - Waste management equipment operation - Release of materials - Waste packages produced for storage or disposal
	Delays, failures, accidents	Cost for mitigation, minimisation or elimination such risks

4.1.4. Comparative CBA

As laid out in section 4.1, the underlying idea of the comparative CBA is to analyse the cost and benefit differences prior to and after the implementation of a measure by different methods to achieve the same result (interim or end-state). By doing this, several cost items which are unknown or difficult to estimate disappear. The main unknown cost items are:

- Value of the situation (site, inventory) prior to the implementation of the measure. This value may be negative (a cost), when the efforts to clear the site from its risk may be higher than the value of the site when all risks are cleared.
- Value of the situation (site, inventory) after implementation of the measure. This value may be negative (a cost), when the efforts to clear the site from its risk may be higher than the value of the site when all risks are cleared.

- Indirect costs independent from the measure when implementing a measure implemented. These costs are costs which would appear anyway e.g. overhead cost from higher level management, which may (but) must not be attributed to the measure.

This is illustrated in the following Table 4.3.

Table 4.3. Calculating the difference building for costs when comparing two methods

Method	Input: Situation (risks/ efforts to be managed) prior to the implementation	Costs of efforts of measure	Outcome: Situation (risks/ efforts to be managed) after the implementation
Method A (e.g. measure with limited RRS)	Value of situation prior to implementation (e.g. risks and costs due to future efforts)	Direct costs of measure by Method A, Indirect costs independent from measure when implementing measure.	Value of situation after the implementation (e.g. risks and costs due to future efforts)
Method B (e.g. measure with advanced RRS)	Value of situation prior to implementation (e.g. risks and costs due to future efforts)	Direct costs of measure by Method B, Indirect costs independent from measure when implementing measure.	Value of situation after the implementation (e.g. risks and costs due to future efforts)
Difference	0	*Difference of direct costs of measure A by Method A and Method B*	0

The difference of direct costs is also an indicative parameter for the difference related specifically to safety because the difference of direct costs includes:

- Difference of human intervention, radiological protection necessary and dose uptake;
- Difference in secondary waste generated;
- Difference in efficiency of waste segregation, sorting, and packaging;
- Difference of emergency preparedness and response needs;
- Difference in time required for implementation and related probability of incidences or accidents.

The cost of implementing a presumably expensive RRS technology needs to be justified economically by the cost savings in these listed parameters, such that the economic justification of the use of RRS typically also includes a gain in terms of safety.

The typical direct main cost elements are described briefly below.

A) Direct costs/expenditures for the implementation of the measure

1) <u>Capital expenditures (CAPEX)</u>

- Investment in human resources: Qualifying staff or hiring qualified staff necessary to implement the measure – e.g. for works by human intervention in radiation areas, for operation and maintenance of equipment (e.g. RRS) performing works in radiation areas (and replacing human intervention)
- Investment in equipment: Includes costs of design, including eventual R&D, licensing, procurement, assembly, testing and commissioning of RRS.

- Investment in supporting infrastructure: Cost of design including eventual R&D, licensing, procurement, assembly, testing, and commissioning of infrastructure necessary to implement, operate and maintain RRS.

2) Operational expenditures (OPEX)

- Labour.
- Cost of qualified staff necessary for operating and maintaining RRS, typically different labour categories (technician, engineers).
- Cost of qualified staff necessary to perform intervention and works in radiation areas.
- Radiation protection: Respecting radiological protection principles including ALARA human intervention requires complementary radiological protection efforts, such as: dosimetry, radiological protection organisation, dose reduction measures, PPE, decontamination and arising secondary wastes, effluent and waste control, radiological protection training, mock-up training of work to be performed in radiation areas. These costs can be listed as separate costs or included in the labour costs for "specialised staff for working in a radioactively contaminated environment". One of the major motivations to opt for RRS may be to minimise radiation exposure (ALARA) and to reduce radiological protection costs.
- Consumables for equipment (eventually also RRS) including: Energy, water, filters, wearing parts, lubricants, other materials.
- Cost for equipment during use, if not already covered by the investment (CAPEX), e.g. for rented equipment or by applying a depreciation rate.
- Maintenance: Includes cost of maintenance, infrastructure, staff, tools, wastes and secondary waste.
- Waste: Includes cost of sorting, classification, packages, packaging, handling, transfer/handover for storage and/or disposal, interim storage, disposal.

B) Cost risks

Cost risk is the risk of exceeding the budget for a project or failing to deliver fair value to offset costs. Risks are determined by the probability of occurrence and possible consequences. In principle, there are also opportunities that formally can be handled as complements to risks. Except for implemented measures to mitigate this risk, the cost risks and opportunities are not material (probabilistic) costs or benefits which will not appear – as long as they are not occurring. Sometimes these risk costs are not analysed in detail but addressed generically. The following risks are typically to be addressed:

- Risk of failure (lack of effectiveness): The probability of occurrence is to be lowered by appropriate provisions against failure during the decision and preparation process. However, there still might be an accepted risk of failure for instance by comparing with a conventional method failure rate. in which an alternative approach (e.g. conventional method). The complementary opportunity would be a complete or improved effectiveness than expected (e.g. use for more operations than initially conceived and expected).
- Risk of low performance (lack of efficiency): Occurrence may be caused by unexpected situations during implementation, insufficiently trained staff, or insufficient support infrastructure to face the implementation challenges. The consequences are typically delays and an increased duration of implementation,

which will increase the costs of time of execution. The complementary opportunity would be better performance (achievement, effectiveness) than expected (e.g. faster or better segregation of components or higher reduction of wastes than initially conceived and expected) and related savings in costs for the time of executions.

- Risk of delays: Occurrence may be caused by inducing events such as listed in the following. The consequences are, if no effective time recovery plan is available, an increase in costs of time of execution.
- Supply problems (for initial equipment, for complementary components, for spare parts, for consumables)
- Availability of adequate staff for operation.
- Availability of adequate supporting infrastructure.
- Inefficient maintenance.

The complementary opportunity would be no delays but faster implementation with related savings.

In the context of the expenditures and cost risks, there are specific cost components which deserve more detail as part of the cost analysis. Such cost components are listed below.

1) <u>Cost of staffing, training requirements, and competence building for RRS</u>

RRS requires qualified and trained staff, requiring ensuring of:

- Availability and training of operating staff,
- Availability and training of maintenance staff,
- Availability and training of reserve staff,
- Availability and training of support infrastructure staff.

Ensuring the above is typically part of human resources management. The accounting of these costs may be included as a specific overhead cost for staff costs (added to the other direct labour costs and normal overheads). It may be also accounted separately a separate cost item (e.g. for a better transparency in this regard). It should be noted that training is an opportunity for reducing risks and for career development of personnel, with the added benefit of increasing motivation. Qualified and trained staff are part of the knowledge and competence assets of an organisation. The latter may be considered as a specific benefit and value for an organisation when utilising RRS.

2) <u>Cost for time of execution</u>

Once the implementation starts, (e.g. investment in equipment, training of specialised staff for implementation or support infrastructure) there are costs related to the time of execution, which are just time dependent running costs such as:

- Cost of staff for implementing RRS (regardless of whether staff is productive or not).
- Cost of support staff (regardless of if staff is productive or not).
- General costs of the site (e.g. security/physical protection, safety, and radiological protection organisation, organisational overhead).
- Cost of financing for investment - depending on the financing scheme, costs may be accounted as partially or fully as a single expenditure over the timeline or as a periodical fee (e.g. periodical rent fee for equipment or infrastructure, lease fee for

an equipment, depreciation plus financing costs, interests to be paid periodically). Depending on the financing scheme costs may be moved between the cost category of capital expenditures (CAPEX) or operational expenditures (OPEX).

- Costs implied by delay of a subsequent site use due to delayed achievement timely measure results.
- Cost risks related to the occurrence of incidents or accident induced by internal or external events which probability may increase with over time until completion of measure.

Saving time (faster implementation) is always an opportunity.

3) Licensing and regulatory process

Licensing and other regulatory processes (e.g. documentation, reporting, inspections) are an implicit challenge for any major activity in the nuclear back-end (e.g. decommissioning, radioactive waste management). The introduction of new technologies may be associated with high efforts and cost risks (due to licensing). Success requires establishing and maintaining a good relationship with the regulator(s) by including transparent, reliable and timely information, preparing documents, and interfacing before, during and after the regulatory processes. This will minimise the risk of delays, reduce confusion and facilitate a stable implementation.

4) Cost of social (political) acceptability

Social acceptability and political acceptability are success factors for implementation. Both the motivation of internal stakeholders (e.g. employees, suppliers, shareholders) and the attitude of external shareholders (e.g. authorities, local governments, national government, local community, communities directly linked to internal stakeholders) may have an impact on decision making, sharing the interest of safe and timely implementation of a specific measure. Thus, acceptability, which may range from rigid reluctancy to enthusiastic support, may have an economic impact. Investment in preferential policy measures to establish and maintain a good interaction with stakeholders may therefore be well-invested costs. Examples are costs to support:

- The general image of improving safety, being up-to-date in advanced technologies, and positive economic and social impacts.
- Information and positive interactions within the public perception and increased perspectives for employees and workers directly involved in the RRS (e.g. “safety agents”, “advanced technologies”, “professional opportunity”).
- Information and positive interaction within the general perception and increased perspectives for other employees and workers on the site (taking ownership of a good activity).
- Information and interactions with neighbours (local community/public) and the general public within the general perception by increasing comfort (knowing and understanding better positive developments at the site in the neighbourhood).

5) Competence and knowledge management

The implementation of highly specialised and advanced systems requires that continuous learning be adopted as a core value of the organisation and implemented at all levels. The performance of a back-end project will depend on a learning curve and the maintenance of competence and knowledge. In this sense, competence and knowledge are assets of the organisation, not only for the current measure but also for the upcoming measures with similar challenges at this or other sites. The value of this asset can be supported by specific measures, such as:

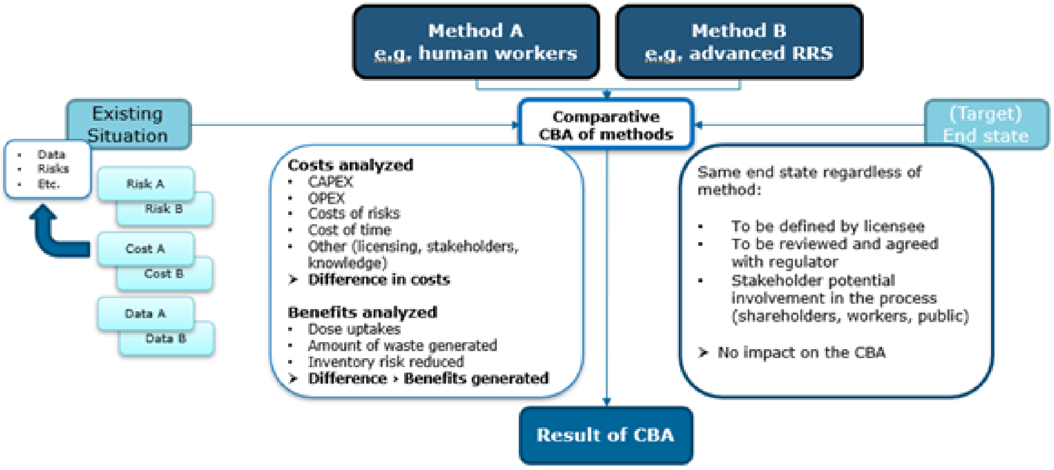
- training, advanced training, and sharing of experiences (within and outside the organisation);
- knowledge retention programmes;
- support (in complement to "normal" operation support) to valorise continued operation (e.g. evaluation of experiences, deep learning, feedback(s), and improvements based on lessons learnt and continued experience).

4.1.5. Examples for comparative CBA

The comparative CBA is applied in the following three examples with the aim of showing the difference between using advanced RRS and following more conventional approaches. For each example two methods, A and B, are used to transform an existing situation into a target situation. These methods are compared in terms of costs and benefits, and by calculating the difference thereof, as described in the earlier sections of this chapter.

This concept is summarised in the following diagram:

Figure 4.4. Concept of comparative CBA



Example 1: Automated waste sorting

Sorting large amounts of bulk wastes of (very) low radioactivity is a common challenge in most nuclear facility decommissioning projects. To minimise the costs of waste management, it is an imperative to sort these wastes into different categories such as for unconditional release, conditional release, very low-level waste (VLLW) or low-level waste (LLW). Beyond the economic impact of the categorisation, sorting also has a safety impact as each category carries its own safety requirements. The conventional method consists in measuring and characterising the bulk wastes in batches via gamma-spectrometric measurement, e.g. with an ISOCS (In Situ Object Counting System) or with a drum scanner. This method tends to be time-consuming, typically requires high-quality equipment as well as qualified workers, and may be suboptimal in precision (e.g. depending on the size and geometry of the batches to be measured).

The use of an automated sorting facility was presented as an example of RRS in the first EGRRS report (see Annex D in NEA, 2023). Such technology has been also presented at the NEA WPTES workshop entitled Innovative Techniques and Technologies to Support Characterisation and Decommissioning of Complex and Legacy Sites, which took place in December 2022 (Presentation 5.1.4 on "Automatic Characterisation and Sorting of Large Quantities of Soil and Rubble" by Felix Langer).

Based on this information, an illustrative example that is close to a real case was summarised in the following table.

Table 4.4. Comparative table, example 1

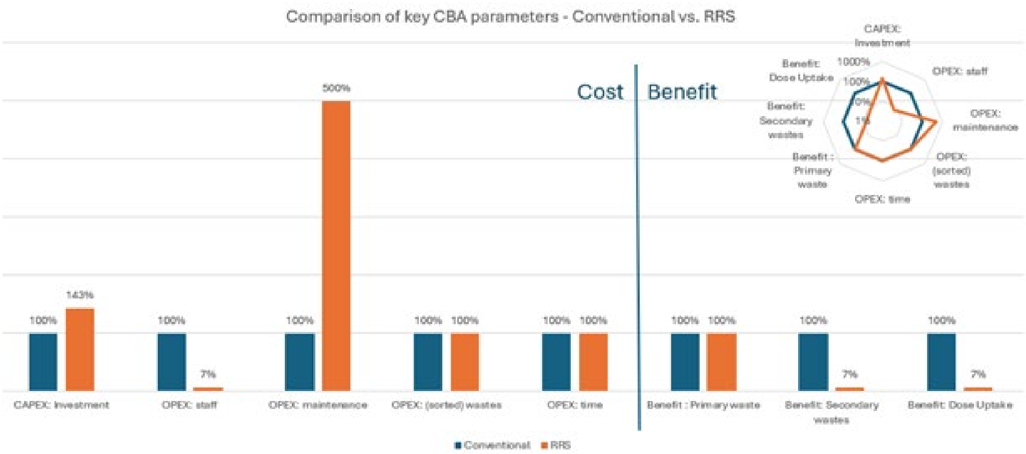
Description	Conventional Method	RRS-Method
Scope	Sort ca. 40 000 tonnes of alpha-contaminated bulk waste from a decommissioning site within 3-4 years into categories "LL-RW", "waste for conditional release", "waste for unconditional release".	
Configuration	Throughput ca. 0.5 t/h per ISOC unit (ca. 1 000 t/y). → for 40 000 t ca. 10 ISOCS units with 6 workers/ unit for batchwise measurement and characterisation over a duration of 42 months	Continuous automated measurement in a moving belt (conveyor) and sorting. Throughput ca. 10t/h (up to 15 t/h) - 8h per day, 5 days per week, 50 effective weeks per year, effective (productive) availability ca. 66% (up to 75%) → 36 months to sort 40 000 tonnes (ca. 13 350 t/y) Requires additionally ca. 6 months for commissioning and testing → Total 42 months
COSTS		
CAPEX	Investment: 10 x 0.7 M€/ ISOCS unit: ca. EUR 7 M	Full Equipment for measurement and sorting with a throughput of 10-15 t/h: ca. EUR 10 M
OPEX	Staff: 10 x 6 workers for 42 months (3,5 y): 60 x 0.1 EUR/y x 3.5 y → EUR 21 M Cost of consumables and maintenance: Ca. EUR 0.1 M /y x 3.5 y → EUR 0.35 M Cost of elimination of sorted waste: Unknown/ not evaluated	Staff: 4 workers for 36+6 months (3.5 y): EUR 4 x 0.1 M/y x 3.5 y = EUR 1.4 M Cost of consumables and maintenance: Ca. EUR 0.5 M/y x 3.5 y → EUR 1.75M Cost of elimination of sorted waste: Same as left (no difference)
Cost of time	Unknown/ not evaluated	Same as left (no difference)
Other (Licensing stakeholders, knowledge)	Unknown/ not evaluated	Same as left, demonstration of performance is included in the 0,5 y for commissioning and testing (no difference)
Comparative CBA	(7 M+ 21 M + 0.35 M) – (10 + 1.75 M + 0.75 M) = EUR 15.75 M cost difference in favour of RRS	
BENEFITS		
Wastes	Primary wastes: ca. 40 000 t Secondary wastes (used PPE): Ca. 60 x 2.5 kg/y x 3.5 y → ca. 0.5 t	Primary wastes: ca. 40 000 t (same as left, no reduction) Secondary wastes (used PPE):4 x 2.5 kg/y x 3.5 y → ca. 0.035 t (ca. 7% of left or ca. 93% reduction)
Dose Uptake	Ca. 1.2 mSv per worker and year: 60 x 1.2 mSv/y x 3,5 Y → ca. 252 man mSv	Ca. 1.2 mSv per worker and year: 4 x 1.2 mSv/y x 3.5 Y → ca. 18,2 man mSv (ca. 7% of left or ca. 93% reduction)

Table 4.4 shows that both methods will not change the driving safety parameter, which is the inventory sorted by both methods. By choosing a configuration equivalent to the same total time of implementation, the main difference is found in staff involvement: by using the RRS-Method, the number of staff (manhours) may be reduced by 97%. This reduction leads to a substantial reduction in costs but also a corresponding reduction in related secondary wastes (e.g. personal protective equipment) and dose uptakes which are safety benefits. An additional safety benefit would be that the reduction of personnel on-site reduces the probability of accidents, in particular those which find their roots in the internal interaction of large groups of staff.

On the other side, the costs for investment and maintenance of equipment will increase but significantly less than the cost reduction for staff.

The main cost and benefit parameters found in Table 4.3 are visualised in Figure 4.5.

Figure 4.5. Comparison of key CBA parameters, conventional vs RRS, example 1



In conclusion, this example shows that the adoption of the RRS will lead to a significant reduction in costs, congruent with a significant increase in safety mainly due to a reduced number of workers involved.

Example 2: Deployment of a multifunctional RRS

In the strategic planning for the decommissioning of a nuclear reactor in Norway, a notable obstacle emerged: the safe removal of radioactive components housed within the containment area. Conventional approaches presented significant risks to personnel, encompassing potential radiation exposure and physical dangers. To tackle these hurdles, a versatile RRS was implemented, harnessing state-of-the-art technology to elevate both safety standards and operational efficacy throughout the decommissioning endeavour.

Deployment strategy

The deployed RRS consists of five sets, each comprising two mobile robots outfitted with LiDAR sensors, radiation detectors, and manipulator arms designed for object manipulation. This system seamlessly integrates into a 3D representation of the nuclear environment, incorporating meticulous radiation mapping. Utilising a cloud-based infrastructure, the system classifies objects based on their radiation levels, empowering the robots to efficiently identify and handle radioactive materials according to their respective radiation levels.

Cost analysis

The RRS system comprises ten mobile robots with manipulator arms, organised into two groups of five robots each. These groups alternate tasks, with one group working while the other charges the batteries. Consequently, the RRS system also includes five charging bases. In total, there are 10 mobile robots, each equipped with manipulator arms, resulting in a total cost of EUR 120 000. Additionally, each robot is equipped with a 3D LiDAR and a radioactivity sensor, with a unit cost of EUR 25 000. The cloud service, which is integral to the system, amounts to EUR 200 000. Furthermore, each group requires five human operators for operation.

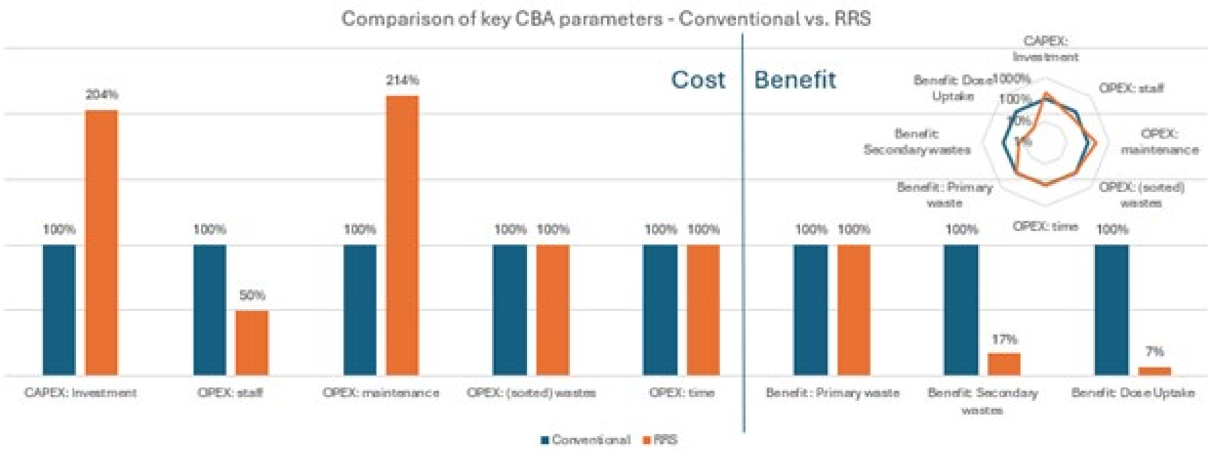
Table 4.5 below compares the Conventional Method with the Remote Robotics System (RRS-Method) for the decommissioning of a nuclear reactor in Norway. It outlines the costs, benefits, and other factors associated with each method.

Table 4.5. Comparative CBA, example 2

Description	Conventional Method	RRS-Method
Scope	**The strategic implementation of a Remote Robotics System (RRS) to ensure the safe and efficient removal of radioactive components during the decommissioning of a nuclear reactor in Norway, integrating cutting-edge technology, including LiDAR sensors, radiation detectors, manipulator arms, and cloud-based infrastructure, while considering a deployment strategy of ten mobile robots organised into two groups, along with associated costs and human operator requirements.**	
Configuration	3 groups of 10 workers in each group	RRS system with two groups
COSTS		
CAPEX	Investment: EUR 0.7 M	Investment: EUR 1.425 M
OPEX	Staff: EUR 2 M Cost of consumables and maintenance: EUR 0.35 M Cost of elimination of sorted waste: Unknown/ not evaluated	Staff: EUR 1 M Cost of consumables and maintenance: EUR 0.75M Cost of elimination of sorted waste: Same as left (no difference)
Cost of time	Unknown/ not evaluated	Same as left (no difference)
Other (Licensing stakeholders, knowledge)	Unknown/ not evaluated	Same as left, demonstration of performance is included in the 0.5 y for commissioning and testing (no difference)
Comparative CBA	(0.7 M + 2 M + 0.35 M) – (1.425 M + 1 M + 0.75 M) = EUR 0.125 M cost difference in favour of Conventional	
BENEFITS		
Wastes	Primary wastes: ca. 65 000 components Secondary wastes (used PPE): Unknown/not evaluated	Primary wastes: ca. 65 000 components (same as left, no reduction) Secondary wastes (used PPE) Estimated 73% reduction due to less personnel
Dose Uptake	Ca. 25.2 man mSv	Ca. 1.82 man mSv (ca. 7% of left or ca. 93% reduction)

The main cost and benefit parameters found in Table 4.5 above are visualised in the following Figure 4.6.

Figure 4.6. Comparison of key CBA parameters, conventional vs RRS, example 2



In summary, the use of a set of ten mobile versatile robots will more than double the cost of investment and the cost of maintenance while significantly reducing the staff costs.

However, the increase in investment and maintenance costs is higher than the savings in staff costs. At the same time there is a significant benefit in terms of safety, primarily in terms of dose uptake reduction but also in the reduced generation of secondary wastes.

Example 3: Use of demolition robot

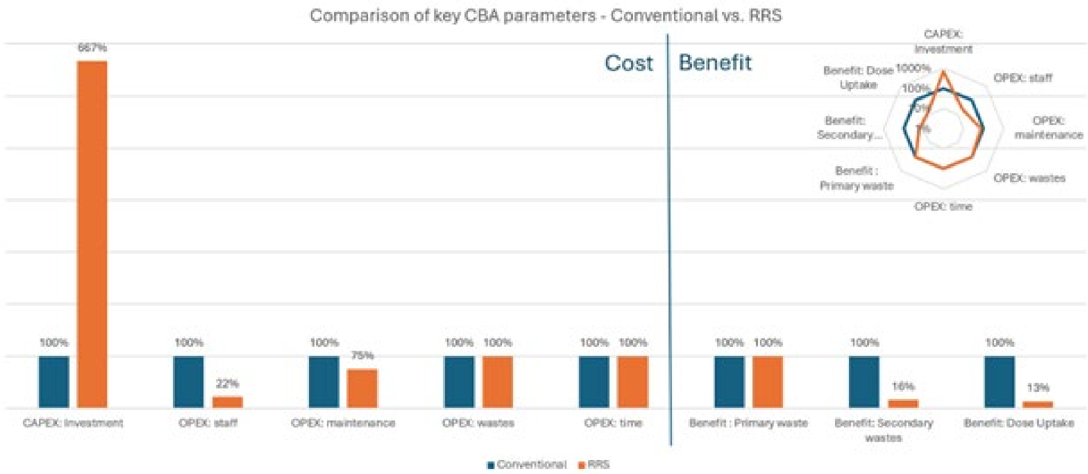
When planning the decommissioning of Ågesta Nuclear Power Plant in Sweden, the removal of the two blowdown tanks with adjacent pipes was one of the main challenges identified. The tanks had a combined weight of around 80 tonnes and were situated adjacent to the reactor hall. Due to the plant being built within a cavern the possibility to lift and remove the tanks intact was impossible. To minimise exposure to conventional and radiological risks it was decided to perform the actual work with a demolition robot.

Table 4.6. Comparative CBA, example 3

Description	Conventional Method	RRS-Method
Scope	**Dismantling of 2 blowdown tanks with a combined weight of around 80 tonnes. The tanks would be cut and dismantled for further packaging in containers.**	
Configuration	Two teams of five workers on each team performing dismantling activities on each tank, each team have access to scaffolders and necessary equipment. Each team works 8 hours a day.	One operator with a Brokk 300 demolition robot with tools designed for metal dismantling, from a safe distance cutting each tank into piece around 1x3 metres and then loading them directly onto carriers for transport directly into waste containers by waste personnel. Both operator and waste personnel work 8 hours a day.
COSTS		
CAPEX	Investment: EUR 30 k/ tools for dismantling: ca. EUR 30 k	Brokk 300 demolition robot with suitable tools: ca. EUR 200 k
OPEX	Staff: 10 workers for 13 weeks: 10 x EUR 2.4 k/w x 13 w = EUR 312 k Cost of consumables and maintenance: Ca. EUR 2 k/w x 13 w = EUR 26 k Cost of elimination of sorted waste: Unknown/ not evaluated	Staff: 1 operator for 13 weeks: 1 x EUR 3.0 k/w x 13 w = EUR 39 k 1 waste worker for 13 weeks: 1 x EUR 2.4 k/w x 13 w = EUR 31 k Cost of consumables and maintenance: Ca. EUR 1.5 k/w x 13 w = EUR 19.5 k Cost of elimination of sorted waste: Same as conventional
Cost of time	Unknown/ not evaluated	Same as conventional
Other (Licensing stakeholders, knowledge)	Unknown/ not evaluated	Same as conventional
Comparative CBA	(30 + 312 k + 26 k) – (200 + 70 k + 19.5 k) = EUR 78.5 k cost difference in favour of RRS	
BENEFITS		
Wastes	Primary wastes: ca. 80 t Secondary wastes (used PPE): Ca. 10 x 10 kg/w x 13 w → ca. 1.3 t	Primary wastes: ca. 80 t Secondary wastes (used PPE): 2 x 8 kg/w x 13 w → ca. 0.21 t
Dose uptake	Ca. 0.06 mSv per worker and week: Higher dose rate due to proximity to tanks 10 x 0.06 mSv/w x 13 w → ca. 7.8 man mSv	Ca. 0.04 mSv per worker and week: 2 x 0.04 mSv/w x 13 w → ca. 1.04 man mSv

The main cost and benefit parameters found in Table 4.6 above are visualised in the following Figure 4.7.

Figure 4.7. Comparison of key CBA parameters, conventional vs RRS, example 3



In summary, the use of a robot for the dismantling of the blowdown tanks allowed the work to be performed more safely and efficiently than would have been possible with conventional methods. The data show that implementing RRS leads to lower overall costs for the work, less secondary waste produced and clear benefits for personnel safety due to the significant reduction of the occupational risks (e.g. crush, trips and fall injuries) as well as a reduction of radiation exposure during the dismantling.

4.1.6. Preliminary conclusions

A comparative CBA may be a pragmatic way forward to justify the use of RRS even if not all cost components are known. By calculating the difference between two options (e.g. conventional method *versus* new RRS-Method) several cost components are virtually cancelled due to subtraction.

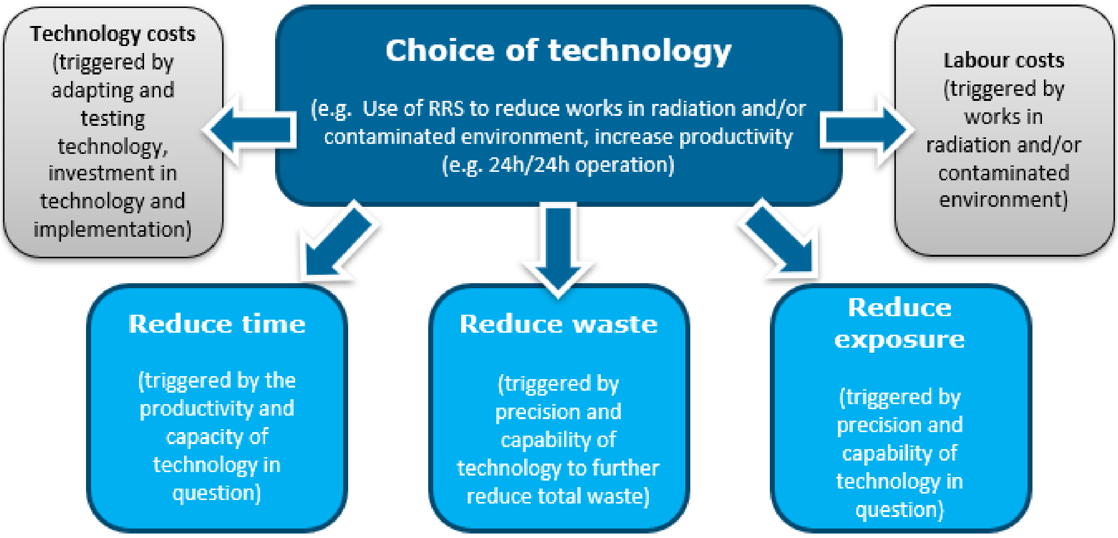
The choice of a technology and its configuration is usually triggered by cost savings, primarily through time reduction, waste reduction, and a reduction of dose uptake (which is typically not evaluated in terms of monetary costs) as summarised in Figure 4.8.

Figure 4.8. Summary of factors triggering adoption of a technology

However, technology comparisons might be difficult as the costs of time and waste are not always known. In such cases, it may be opportune to treat the time factor as a constant (or neglect the cost of time at a first glance) and to focus on the specific costs implied by the specific technologies. These are typically initial investment, maintenance and staff costs.

The key triggers for choice of technology may be further differentiated for the CBA, as seen in Figure 4.9 below.

Figure 4.9. Overview of CBA main cost and benefits



As shown in the examples, the use of RRS will typically imply high initial investments and maintenance costs and reduced staff costs. On the safety benefit side, the use of RRS typically reduces the amounts of secondary wastes generated and the dose uptake.

5. Conclusion

The EGRRS strives to anticipate the future needs of the nuclear back-end. As the adoption of robotics and remote systems could be a game changer, the EGRRS finds it critical to support their implementation. It is with this mindset that the group established the programme of work of their second mandate, whose results are reflected in this report.

The licensing workstream aimed at gaining insights on opportunities for improving this process by sharing areas of good practice between countries. The collection of ten international case studies and additional group discussions made it possible to identify enablers and blockers (or perceived blockers) to innovation in the regulatory permissioning/licensing process.

The cases studies also highlighted some good practices such as:

- Lessons learnt exercises involving regulators and licensees, which could provide a positive way to reflect on challenges and opportunities emerging from licensing.
- The necessity to have long-term and appropriate engagement strategies between stakeholders.
- The use of inactive mock-ups (including digital twins) or active demonstrators, which could provide a good opportunity to de-risk the final licensing of a full-scale plant involving innovative solutions.
- The implementation of a robust defence in depth to provide a positive means by which solutions imported from other less hazardous industries can be safely deployed in the nuclear energy sector.
- Upfront work on the safety case to consider safety in parallel to the design from early stages of development.

The benchmarking workstream was conceptualised to tackle one of the primary challenges to the adoption of innovative technologies: proving the level of readiness and reliability of the RRS and collecting user experience data. As the data need to be both high-quality and consistent, the EGRRS believes that one of the solutions is to build a benchmarking database. Applying traditional benchmarking approaches to the nuclear sector, however, proves challenging due to the absence of defined "reference cases". Each country and site operates under distinct interpretations of international regulations, different local cultures, and varied and unique technical challenges. This inherent diversity renders the conventional benchmarking methodology impractical. The proposed approach focuses on the fundamental tasks associated with decommissioning and waste handling. The EGRRS found four main categories:

- mapping/measurement and investigation;
- decommissioning works;
- material and waste handling;
- revision/service.

The EGRRS also established a grading system, assessing whether a system has been demonstrated or extensively used with lessons learnt available, and theorised a step-wise methodology to allow for fair and balanced assessment from experts, with the possibility for solution developers to reply to criticisms and requests before data are uploaded to the system. The EGRRS hopes to make this concept a reality and will strive to further detail the business plan and draft the technical requirements for the database in the next mandate period.

The cost-benefit analysis workstream emerged as a response to the lack of costing data, which made it difficult to justify investment in new technologies deviating from the status quo. A specificity of the nuclear back-end is the fact that there are no traditional “returns on investment” in the form of financial profit. The main economic benefits of an investment would be primarily the value of generated safety, saved costs and the value provided by the reuse of a site, if any. Another specificity is the complex nature of most back-end sites. These projects typically deal with unexpected deviations and complications which make it nearly impossible to anticipate an accurate and comprehensive financial assessment of all the costs. A comparative CBA, subtracting the common unknowns from all the different scenarios, and fixing the end-state, is a pragmatic way forward to justify the use of RRS, even if not all cost components are known.

These intermediate conclusions confirm that successful implementation of RRS results not only from technological developments, but from a holistic approach that takes into account regulation, availability and trust in technical data, as well as sound business cases.

After summarising and analysing the findings, the EGRRS identified follow-up actions and topics for the next mandate. First, the EGRRS will be further investigating the creation of a benchmarking database by identifying experts willing to conduct the assessments and organisations willing to fund the initiative. Second, as it appeared clear that solution developers, back-end site operators, waste management organisations and regulators need a neutral forum to share perspectives and identify best practices in success stories together, the EGRRS decided to join action with the NEA Working Party on Technical, Environmental and Safety Aspects of Decommissioning and Legacy Management to organise a joint workshop dedicated to the implementation of innovative technologies to back-end sites. Third, the EGRRS also identified the human aspect as critical to successful implementation, in particular with regards to training and knowledge management. Thus, the EGRRS is launching a series of public webinars to share lessons learnt with the wider robotics and nuclear community, including students.

Appendices

Appendix 1: Test cases for section on regulation

A.1. Test case from Norway/IFE

Who was interviewed

Petter Leira from Institute for Energy Technology (IFE). He is working as a physicist and researcher. He is working in the project "RoboDecom" as a radiological protection expert, consulting and applying knowledge to the project.

Description of the project

The "RoboDecom" project is about how robotics can be applied in nuclear decommissioning. The project also introduced the idea of how the robot "SPOT" by Boston Dynamics can be valuable and make for example radiological and physical characterisation easier and autonomous. The goal is to use the decommissioning of the Halden Reactor for research and as a test case for robotics. The project has also successfully deployed SPOT in a small section of the facility, but for marketing purposes.

Figure A1.1. Advancements in unmanned vehicle technologies and remote operation systems

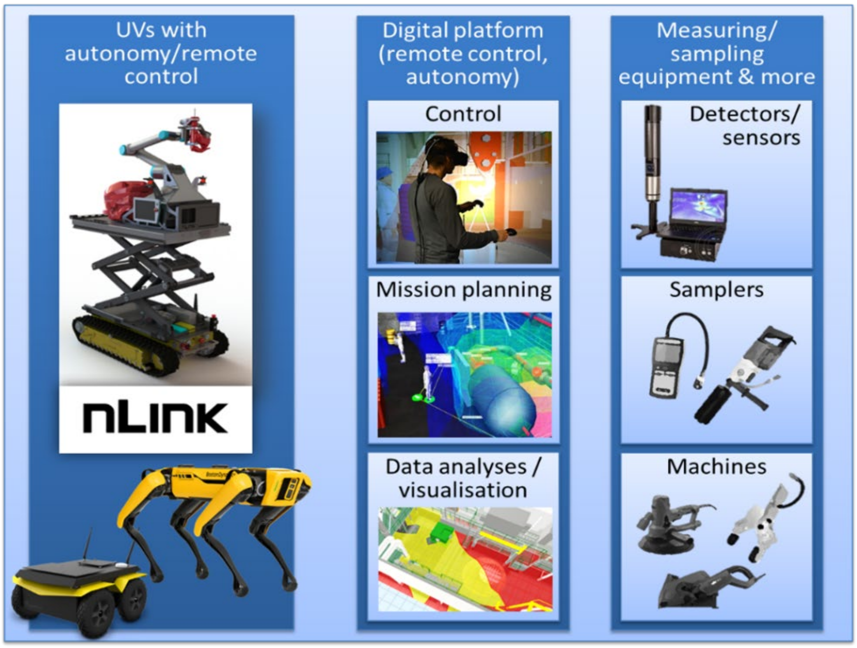


Figure 1. IFE team overseeing SPOT's operation

Type of solution/technology (fully automated/autonomous, supervised, teleoperated)

SPOT is a teleoperated quadruped robot. It can, however, become a fully autonomous robot. That is what we also are investigating in the project. There are also other types of robots in the project.

Stage in the development (initial research at university level up to ready for deployment – incl. technology review level/TRL)

Ready to test and be deployed in the nuclear facility of IFE that is getting ready for decommissioning. However, regulatory control and safety issues prevents the project to deploy the robots.

Safety function (or not)

Has an emergency stop. Both on handheld teleoperated device and physically on the robot.

Safety functions placed on other equipment as a result of the use of robotics

Has sensors and depth cameras with integrated anti-collision software. Other than that, our HADRON-lab (robotics lab) is fully equipped with safety functions for our robots. There are no safety functions in place at the reactor site, other than contamination protection for the robots.

Safety/ radiological consequence of spurious operation

Robot or supportive systems getting hacked causing sensitive information to leak or get out.

Safety/ radiological consequence of fault operation – not doing something it should

Bump, crash or fall onto something and potentially damaging something within the facility, personnel, damaging or destroying the robotic unit itself, or get contaminated and produce secondary waste.

Challenges/learning from the permissioning (or foreseen if in the future)

Timing of engagement with regulators

Better communication and guidelines need to be provided or established with the regulatory authority. Especially for the operators. For the deployment of SPOT, we just needed approval from the operators at the site, but they themselves were unsure of where and how we could deploy the robot. Since it was just for marketing purposes, an area of low significance was chosen. For future reference, detailed guidelines for the use of robotics in the nuclear facilities needs therefore to be established.

Different possible stages

- No valuable information here. The area was chosen based on operator experience, and no involvement of the regulatory authority. More guidelines on implementation of robotics needed.

Technical challenges

Novelty/complexity of more extreme /innovative applications (e.g. from universities)

- Transfer of data from robot to computer. The robot needed to be connected to the computer through a long ethernet cable, which can be hazard itself. From the operator side, it was understandably not allowed to implement wireless transfer of data.

Design processes employed/systematic approach, including supporting evidence

- No challenges were faced in the design process of this task. The decision of deploying the robot was done quickly, and the operator agreement was also done quickly. For other tasks, such as decommissioning work, the potential of stumbling upon other technical challenges and uncertainties is much larger, as there are no clear guidelines from both operator and regulatory side.

Challenging areas in the submission supporting permissioning (cybersecurity, engineering substantiation, maintainability, fault recovery, secondary waste and sustainability)

There was no submission for permission to use robotics in the facility to the regulatory authority of Norway, only to the operators themselves. We see, however, that especially cybersecurity, fault recovery and secondary waste being potential challenging areas in the permission submission. Another challenging area here is the time spent for approving the submission from the regulatory side.

Availability of suitable standards/designed or certified against applicable standards

- None available from the regulatory authority in Norway.

Uncertainty in regulatory expectation

High uncertainty because of communication issues. The regulators, operators and R&D scientists do not have sufficient communication for issues like this. No guidelines.

Human factors considerations, including SQEP operators/supervisors

No particular challenges or lessons learnt from this case study.

Any other recommendation from this perspective

Any areas of improvement – blockers

Regulatory uncertainty: with complete guidelines and better and open communication with the regulatory authority, implementation of innovation and test cases with robotics can be done in an easier and safer way in terms of regulatory independence.

Any other recommendation – enablers

Demo/prototyping/mock-up: Implementing software, for instance training simulations, for human operators and robotics. Develop scenarios in a virtual environment to showcase risks and solutions before implementing it in the physical world. Could also be a part of the permissioning process.

A.2. Test case from the United Kingdom/Sellafield Limited

Who was interviewed

- Michael Donnelly (RE for BEP, similar application)
- James Morris (RE for EPS-WTR)

Description of the project

Kuka robot utilised for the process of removing bolts and lids from a 3 m^3 box and then re-lidding and bolting the boxes. Process follows a pre-programmed taught path for the robot operations. Systems includes integration with nut runner tool (different supplier) to provide overall functional requirements.

Type of solution/technology (fully automated/autonomous, supervised, teleoperated)

System utilises reasonably traditional wider industry automation technology, but novel for nuclear industry. No real autonomy in use for this system. Process employed to date requires operator initiation and supervision of the completed actions to confirm to provide the overall confidence of task completion.

Stage in the development (initial research at university level up to ready for deployment – incl. technology review level/TRL) –

System has been deployed to complete a limited number of products meeting the success criteria. There have been a number of unsuccessful operations but this is thought to be due to the boxes/lid tolerances and not related to the robot performance, as per the design intent.

Safety function (or not)

Minor safety function on nut runner tool only, no safety function directly associated with robot.

Safety functions placed on other equipment as a result of the use of robotics

Safety function claimed on the operator to confirm the robot operation. Minor claims in safety case on independent tool used to confirm nut runner performance, smart device but not related to robot (other than robot placing the tool in the device).

Safety/ radiological consequence of spurious operation

None known, in-cell operation only, zero human interaction during operations, limited interaction during commissioning. Cell structure provide overarching shielding/containment and guarding functions.

Safety/ radiological consequence of fault operation

Limited by operator supervision. Failure on both robot and operator to confirm correctly completed operations would be limited in terms of direct radiological consequence. Possibility of product quality issues leading to future problems with stores, mainly leading to loss of process availability.

Challenges/learning from the permissioning

Timing of engagement

Engagement was late but good reason – due to initial normal plant designation, safety requirements changed mid-way through project design (mostly due to ONR challenge on an upstream plant). Decision to use a robot was established at programme level as part of project specification, due mostly to LFE from other similar plants and expected "short-term" nature of the overall facility.

Technical challenges

1. SL understood the design/technology – but there was some difficulty in addressing the exact safety requirements and assigning the claims to the correct part to the technology.
2. Several questions raised over what are the enabling parts of the systems that require the overall safety function technology, i.e. nut runner, robot, vision system, etc. what is the essential part?
3. Robots still seen as novel and stakeholder challenge can be over-intrusive for specifics on the technology leading to problems with releasing IPR and detailed information. Questions raised over what level of information do ONR need over what do they think they need or are just interested in?
4. Technology was reasonably ok to understand at what SL believed the right level to carryout IC oversight.
5. Wider interest in the underpinning of the requirement on the robot took a long time, this was the number of bolts and torque values that were required, not really part of the robot problem.

Challenging areas in the submission supporting permissioning (cybersecurity, engineering substantiation, maintainability, fault recovery, secondary waste and sustainability)

1. 5-year maintenance free strategy meant limited challenge on maintenance
2. Recovery was considered, document produced of fault scenarios had already considered was made available

Availability of suitable standards/designed or certified against applicable standards

1. Machinery safety/CE marking only – wider system integration issues over strategy and envelope of the machine/system.
2. Supplier high confidence in equipment is difficult to communicate to regulator, despite wider industry LFE.

Uncertainty in regulatory expectation

Initial uncertainty was resolved quickly once dialogue established between the project. Advantages in maintaining consistent persons, having the communication routes clear from the beginning and agreed with the project.

Human factors considerations, including SQEP operators/supervisors

Limited ONR questions on HF but project did provide significant information for the whole process. Generally, this was a relatively simple and self-contained operation with few interactions with different systems.

Any other recommendation from this perspective

- Staged permissioning ("banking" of decisions) – Would have been useful but not conserved at the time due to the rapid project delivery that was attempted, maybe it did not work out that way.
- Demo/prototyping/mock-up – Works testing included a mock-up cell that was very useful.
- Skills: No real training issues, training was made available at reasonable cost and time etc however upskilling issues noted around the turnover of people encountered. Due to career development and progression and general business needs. Individuals with certain skill sets identified to help commissioning and early project phases and the type of people how can support other parts of the business and have ambitions to progress. Maintaining a core team at the start of ops was difficult but has settled now.
- Engagement with regulator/regulatory independence: also noted on how the final review occurred, ONR being supportive of the approach due to the close working to that point before gaining wider "independent" assessor approval.

A.3. Test case from the United Kingdom/National Nuclear Lab

Who was interviewed

- Stephen Shackleford - Head of Capability Nuclear Operations, NNL.

- Howard Chapman - Principal Radiological Safety Consultant, NNL.

Description of the project:

- The original concept of using a combination of robotic and laser cutting technologies in of itself was not novel – however, it was not commercially available. As a robotic laser cutting was first-of-a-kind (FOAK), technology research funding was required to support its development.
- In 2013, NNL in partnership with LOE (Laser Optical Engineering Ltd)/ULO/TWI (The Welding Institute) secured grant funding through the Innovate UK TSB (Technology Strategy Board) to develop an in-cave active laser cutting station for the size reduction of intermediate-level waste (ILW) arisings for the NNL Windscale Laboratory (see Figure A1.3) and across the Sellafield Ltd (SL) estate. The aim was to represent a major contribution, and a step change to accelerate the United Kingdom's decommissioning programme.
- In 2016, a commercial decision was made to deploy an active robot laser cutting system demonstration facility at the NNL Preston Laboratory (see Figure A1.3, A1.4, A1.5 and A1.6.) This was commensurate with a partnership between ARM Robotics Ltd and NNL for the introduction to deploy semi-autonomous robot laser cutting.

Type of solution/technology (fully automated/autonomous, supervised, teleoperated)

- The Robotic 5 kW laser cutting station system deployed at NNL Preston Laboratory consisted of a KUKA KR 20-3 robot, with an associated KUKA KR C4 robot controller. Laser cutting was achieved using an IPG Photonics laser, with a ULO laser head mounted to the end effector of the robot. Additionally, during the semi-autonomous laser cutting process, a Microsoft Kinect was used for performing point cloud scanning of objects to be cut (Figure A1.5).
- Operation of the laser cutting system was possible through two modes; i) a manual mode, where cuts were pre-planned by operators along a fixed path; and ii) a semi-autonomous mode, where the cutting path was calculated by software between two operator selected points.

Stage in the development (initial research at university level up to ready for deployment – incl. technology review level/TRL)

- Individually, lasers and robots have existing provenance gained from operations outside of the nuclear sector. Therefore, robots and lasers have developed a relatively high TRL (Technology Readiness Level).
- NNL has existing provenance of remote handling operations and of hot/cold cutting gained from operations within the NNL Windscale Laboratory Cave system.
- NNL's Workington inactive facility is also utilised for testing, training and pre-commissioning.
- The active deployment of a FOAK combined Active Robot Laser Cutting station at NNL Preston Laboratory aimed to progress the TRL from TRL 3, through demonstration in a relevant environment up to TRL 6. This would thereby allow its exploitation across the Sellafield and NDA estates.

- The semi-autonomous system developed by ARM Robotics Ltd was a technology spin-off from the University of Birmingham; with the aim to progress the technology from low TRL to active deployment.

Safety function (or not)

The safety function considered was detailed as follows: i) Interlock Systems; ii) Containment – with detailed assessment on radiological and chemotoxic; iii) Supervision; iv) Training; v) Management Controls, and vi) PPE.

Safety functions placed on other equipment as a result of the use of robotics

- Containment of the Active Robot Laser Cutting station.
- Interlock systems of the robot and laser.

Safety/ radiological consequence of spurious operation:

- Assessed as part of HAZOP (Hazard and Operability) and detailed assessment covering conventional and Radiological hazards etc.
- The main safety concerns raised were as follows: i) Class 4 lasers; ii) Respirable fume generated from hot cutting; iii) Potential for Fire and Explosion; and iv) Control of remote operations.
- Safety/ radiological consequence of fault operation – not doing something it should
- The main consequences were outlined as: i) Potential for fire and explosion; ii) radiological/chemotoxic release due to blinding of filters; and iii) damage to containment facility.

Challenges/learning from the permissioning (or foreseen if in the future)

Timing of engagement with regulator; based on complexity, maturity, uncertainty, safety significance, consequences

The main challenges associated with laser technology (fume generation, filtration etc) are not outlined in this test case.

- Different possible stages (optioneering vs concept design vs detail design)
- NNL's project design process was followed for Engineering, Electrical, CDM (Construction, Design Management), Ventilation, Software etc.
- This comprised of: Optioneering, Preliminary schematic design, Detailed design, Inactive testing, active build and commissioning.
- Design (Electrical, Mechanical, Safety case etc), Safety, Financial, etc. gated processes were followed throughout the project lifecycle.
- Reviews were undertaken for all aspects of the project including plant design, mechanical deployment, cutting system and system architecture for robot operation.
- The optioneering reviewed all cutting technologies and deployment systems – Mechanical /plasma/laser and remote deployment systems. The eventual laser and robot were chosen from optioneering, and concept designs generated (see Figure A1.3 and A1.4).
- The completed design at NNL Preston Laboratory is provided in Figure A1.5.

- HAZOPs 1 and 2 and Safety Case were produced for NNL Preston Laboratory, and Hazard Review for NNL Workington Laboratory and Safety Case.

Technical challenges

Novelty/complexity of more extreme/innovative applications (e.g. from university)

- Operating a Robotic high-powered laser cutting technology within a cave environment.
- Development of laser system with automatic laser cutting.
- Development of semi-autonomous system for robot laser cutting.

Design processes employed/systematic approach, including supporting evidence

- NNL's project design process was followed for Engineering, Electrical, CDM (Construction, Design Management), Ventilation, Software etc.
- This comprised of: Optioneering, Preliminary schematic design, Detailed design, Inactive testing, active build and commissioning.
- Design (Electrical, Mechanical, Safety case etc), Safety, Financial etc. gated processes were followed throughout the project lifecycle.

Challenging areas in the submission supporting permissioning (cybersecurity, engineering substantiation, maintainability, fault recovery, secondary waste and sustainability)

- Areas of challenge related to the laser system were off gas and filter blinding.
- Additional trials were undertaken to assess the impact on building ventilation.

Availability of suitable standards/designed or certified against applicable standards

The list below is not an exhaustive list of standards that were engaged with as part of the review:

- Health and Safety at Work Act.
- EN ISO 13849 (safety of Machinery, Safety related parts of control systems, General principles of design).
- EN 62061 (Safety of Machinery functional safety of safety related electrical electronic and PES), which is based on IEC 61508.
- The Supply of Machinery (Safety)(Amendment) Regulations 2011
- Laser safety.
- European Standard EN 60825-1:2007, Safety of laser products – Part 1: Equipment classification and requirements.
- EN ISO 11553-1:2008, Safety of Machinery-Laser processing machines
- Robot safety
- COSHH Regulations. COSHH data sheets will be required where applicable.
- Factories Act.
- The (CDM) Construction, Design and Management Regulations.

Uncertainty in regulatory expectation – No Comment.

Human factors considerations, including SQEP operators/supervisors

These were considered as part of the project, with management control and SQEP training provided for robotic/laser operations.

Any other recommendations from this perspective

Any areas of improvement – blockers

No Comment.

Regulatory independence vs regulatory uncertainty

No Comment.

Engineering substantiation vs functional hazard assessment

No Comment.

Balance of risk and ALARP arguments

The Hazard Management Strategy (HMS) followed a hierarchical approach to safety measures (i.e. Eliminate Reduce Isolate Control Personal protective equipment Discipline) used to minimise or eliminate the exposure to hazards:

- Elimination of the hazards wherever possible,
- Reduction of the hazard by substitution with a less hazardous form if possible,
- Isolation and Control of the hazard with Passive/Engineering controls to prevent/mitigate the hazard where appropriate,
- Reliance upon Personal protective control to mitigate the hazard, and Discipline with procedural controls is the ‘last line’ of defence.

Any other recommendations – enablers

- Staged permissioning (“banking” of decisions)
- Demo/prototyping/mock-up
- Inactive demonstration and prototyping were key to the successful deployment from an engineering/software/safety perspective, but also financially.
- FOAK deployments require substantial modifications, although with greater use of robotic systems COTS robotics have increased flexibility and operator provenance in support of nuclear deployment.
- Expert panel/sandboxing
- Increased requirement for supplier expertise to support the implementation of robotic technology and ongoing maintenance of software/hardware.

Questions

How to upskill in an efficient way and identifying areas where upskilling is required

No Comment.

How to raise awareness of future applications in R&D

No Comment.

Figure A1.3. Original concept design at Windscale isometric view proposal layout

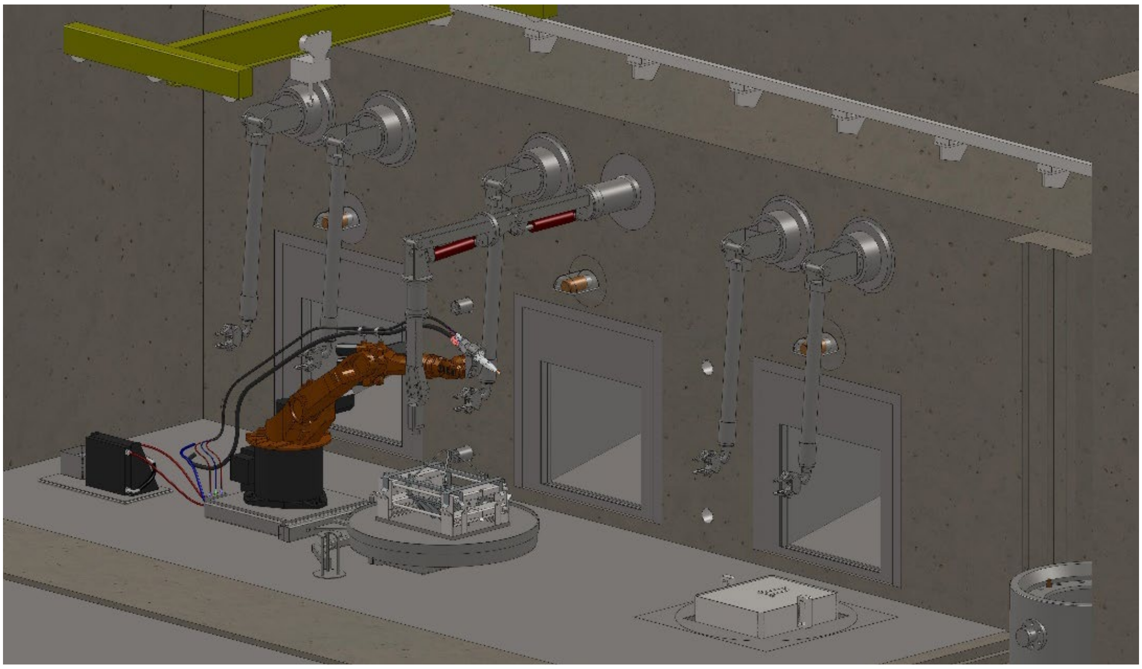


Figure A1.4. 3D CAD model showing setup of the laser active cutting station at Preston

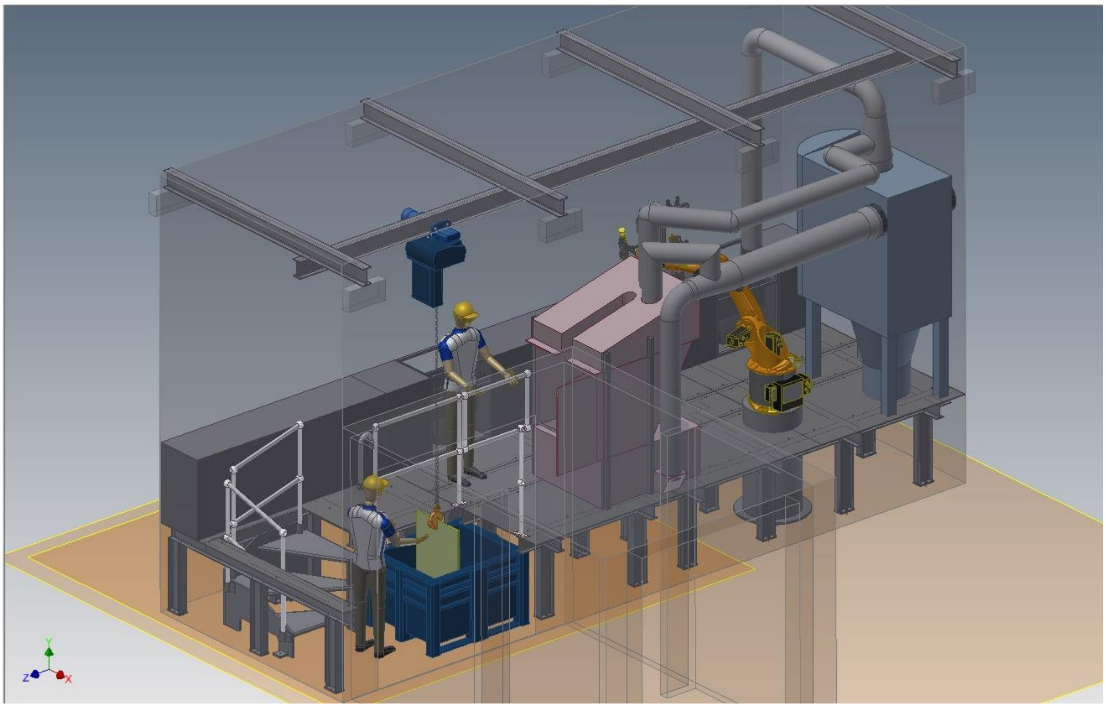


Figure A1.5. Laser cutting 304 L 6 mm thick plate during rig commissioning

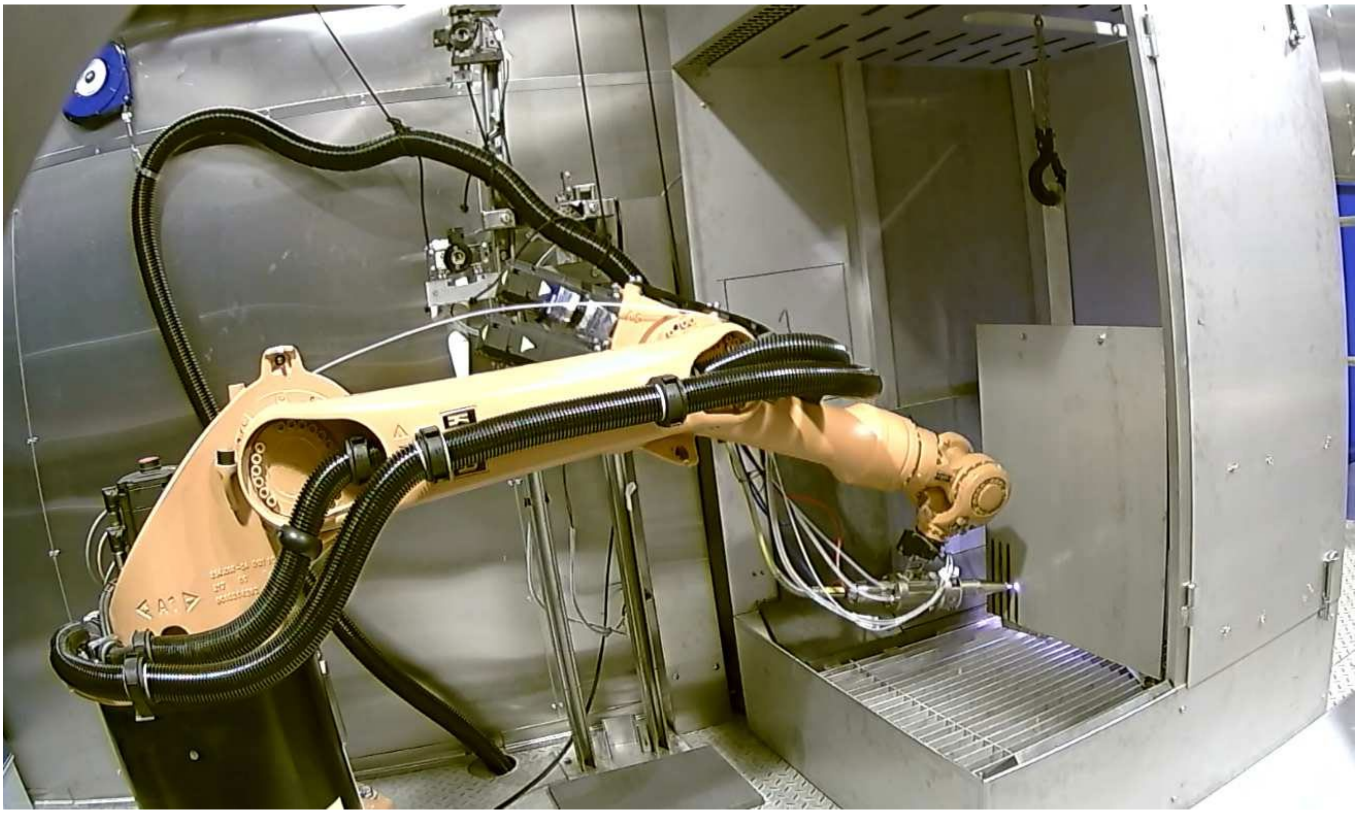


Figure A1.6. Photo of the operator workstation

Showing CCTV footage and thermal camera image of the cutting station at Preston

A.4. Test case from Canada/CSNC

In Canada, the responsibility for ensuring safe transport of nuclear substances is jointly shared between the CNSC and Transport Canada. Transport Canada's *Transportation of Dangerous Goods Regulations* (TDGR) deal with the transport of all classes of dangerous goods, while the CNSC's *Packaging and Transport of Nuclear Substances Regulations, 2015* (PTNSR) are primarily concerned with health, safety and security of the public, and protection of the environment related to the special characteristics of radioactive material. Both the TDGR and PTNSR apply to all persons who handle, offer for transport, transport or receive nuclear substances. The requirements of the PTNSR and TDGR currently cover all modes of transport, including the use of drones. Aerial drones are considered aircraft and are also regulated under the Canadian Aviation Regulations (CAR). Drones must operate in accordance with all rules established by the CARs.

There is nothing in Canadian regulations to prevent the transport of radioactive materials using an arial drone. The proponents must ensure all applicable requirements from these regulations are complied with. If deemed necessary, the CNSC can propose future amendments to the regulations based on experience gained from aerial drone transportation.

To that end, in Canada the delivery of medical isotopes directly from the reactor to the site. This is unique from the regular use of drones for delivery because many medical isotopes have very short half-lives and are shipped on a just-in-time basis. In fact, for some isotopes, a 20-minute delay in traffic can mean sufficient decay to render the product useless. To address this issue, after a successful pilot project, McMaster University, Drone Delivery Canada, DSV Logistics and Halton Health Care are now transporting medical isotopes from the McMaster University Research Reactor in excepted, or Type A packages between a carrier facility and a hospital.

CNSC inspectors are conducting regular compliance verifications to ensure that consignors and carriers comply with the requirements of the PTNSR and TDGR. They verify proof of training for transport workers, review transport documents and inspect packages to ensure they are prepared for transport in accordance with regulations. If a licensee or carrier is found to be non-compliant with these regulations, the CNSC uses a graded enforcement approach for the implementation of corrective measures.

In addition, any accidents, or dangerous occurrences due to the use of aerial drones which are transporting nuclear substances must be reported to the CNSC. If any negative trends are observed related to the frequency of accidents or the severity of accidents, the CNSC can take appropriate regulatory actions such as issuing orders or administrative monetary penalties.

As new and innovative ways to operate are explored, the CNSC continues to use a risk-informed approach to regulation and remains committed to ensuring the health, safety and security of the environment and the Canadian public.

Figure A1.7. Flight path of the drone

Figure A1.8. CNSC staff oversee the preparation of a drone being used to transport medical isotopes

CNSC exploring the use of drones for licensing, inspection, and compliance inspections

As licensees continue to adopt the use of drone and robotics technology in their activities, the CNSC is interested in exploring the potential for drone/robotic technology as a tool in the CNSC's compliance activities. To that end, the CNSC has commenced a research project to explore the use by its staff of drones for the following applications.

Test Case 1: Marine sampling

As part of the CNSC's Independent Environmental Monitoring Program, staff take water samples in a variety of environments. This could be from shore, from a dock, from a pier, or occasionally from a boat. There are many locations where it is either not feasible, or not safe to sample from shore. This results in changing sampling locations or occasionally taking lower quality water samples (in marsh land, stagnant or shallow water). For some sites, the CNSC will work with the licensee to sample by boat. This complicates the logistics and creates additional health and safety risks. Using a drone could facilitate better quality and safer water sampling in many locations. The feasibility of utilising an aquatic drone to collect these samples will be explored.

Case 2: Remote sampling

Currently, as part of the CNSC's Independent Environmental Monitoring Program, CNSC staff are only permitted to take samples in publicly accessible areas. At many sites, there is a large amount of private property around the facilities making it difficult to access good sampling locations. There are also locations where it is not safe to access the shoreline on foot due to bluffs, cliffs or unstable terrain. This results in accessing the sampling locations by other means (boat, hiking in from safer access points) or by sampling in a less desirable location. The ability to access locations by aerial drone will be explored would alleviate these logistical and health and safety concerns.

Test Case 3: Monitoring of mine and mill sites

Currently, as part of the CNSC's compliance activities, both historic and active uranium mines and mills (UMM) are monitored. These sites are often in remote locations and travel to these sites can be arduous and expensive, especially with the decommissioned and historic sites that lack infrastructure. UMM sites often have large footprints and could benefit from arial composite images of large structures such as tailings management facilities, waste rock piles, dams and other earthworks. A method to map radiation surveys to these images would also be desired. Further, thermal imagery of dam structures could be utilised to assess dam integrity.

Due to the location and ecology of UMM sites geological structures are often vegetated, a method to image the earthworks free of vegetation would be desirable. Furthermore, a method to evaluate vegetation would also be desired. Current vegetation evaluation methods are entirely subjective and based on inspector observation.

Test Case 4: Observing security exercises.

Currently, CNSC staff rely on visual observations, photos and video taken during the Force on Force (FoF) exercises at nuclear facilities, to support post-exercise review and evaluation of the FoF. It is thought the use of drones would benefit as follows:

- Aerial Evaluation:
  - Before Conducting FoF:
    - Provide accurate site layout for determination and development of scenarios to be used during the FoF. Capturing of videos taken by drones may also allow for dynamic information to be retained for use in scenario design.
  - During Conduct of FoF:
    - Augment existing CNSC staff observations by providing an aerial view and footage of the movements of Canadian Adversarial Testing Team (CATT) and licensee's nuclear response force (NRF).

Test Case 5: Construction activities

Currently, CNSC staff must observe construction activities in-person from the ground and observation may be limited to specific vantages due to site safety procedures. The CNSC is seeking to utilise drones/robots to augment the current observation methods and improve data collection and record keeping due to the time sensitive nature of these activities.

The CNSC hopes to complete the research project by the spring of 2024 at which time a determination will be made as to how to progress.

A.5. Test case from Italy/Sogin

Brief Summary of licensing process in Italy

The decommissioning of Italian nuclear sites and the management of radioactive waste are activities subjected to authorisation and approval procedures, involving the Ministry of Economic Development (now MIMI), the National Inspectorate for Nuclear Safety and Radiation Protection (ISIN), the Ministry of Environment and Energy (MASE) and other national and local institutions.

The main authorisation act for the dismantling of a nuclear plant is the Deactivation Decree, issued by the Ministry of Economic Development, after hearing the opinions of the MASE, Ministry of Home Affairs, Ministry of Work and of Social Policies, Ministry of Health, the Region concerned and ISIN. This procedure, envisaged by the articles 55 ("Authorisation for the deactivation of nuclear plants") and 56 ("Procedure for the issue of the authorisation for deactivation - Conduct of operations") of the Legislative Decree No. 230/1995[1], starts with the presentation by SOGIN of the Request for Deactivation[2].

Pending the release of the Deactivation Decree, individual projects may also be authorised for the purpose of carrying out the decommissioning and temporary works and temporary structures necessary for decommissioning (i.e. new facilities, interim storage building of RaW, etc.). In particular, the authorisations on the single projects can be obtained through the application of the following articles:

- Article 148, paragraph 1 bis of the Legislative Decree 230/1995 for particular operations and specific interventions, even if related to deactivation, aimed at ensuring the most effective protection of workers and the population;
- Article 6 of Law no. 1860/1962, for activities concerning specific requests of control Bodies/Organizations and for plant modifications that may consist in the realisation of new works or in the modifications of plant systems, important for safety.

Having obtained the Deactivation Decrees or the authorisations envisaged by art. 233 of the Legislative Decree No. 101/2020, SOGIN is required to submit specific operational plans (PO) or project reports (RPP)[3] to the ISIN for approval, in which the work to be carried out and the appropriate assessments on safety and radiological protection are described[4]. The Deactivation Decree represents the "Top Level" authorisation. In the absence of a deactivation decree, SOGIN can apply for approval of specific projects to the ISIN but in this case the first level authorisation can be replaced by the opinion of the "Conference of Services"[5].

[1] The legislative decree n. 101/2020, published on 31 July 2020, transposes Directive 2013/59/EURATOM, rearranging and updating the previous Italian legislation in a single text in field of radiation protection, which also includes D. Lgs. No. 230/95, which was the previous regulatory reference. Legislative Decree No. 101/2020 is the main law regarding nuclear installations in Italy and their licensing.

[2] "Istanza di Disattivazione".

[3] The so called "Rapporto di Progetto Particolareggiato" (RPP) is a summary document which, depending on the case, derives from the basic design or the preliminary project/feasibility study.

[4] The level of detail depends on the specific project.

[5] The Conference of Services (Conferenza dei Servizi) is an institution of Italian legislation which has the purpose of facilitating the acquisition by the Public Administration of authorisations, deeds, licenses, permits and authorisations or other elements however denominated, by convening

With regard to the environmental aspects, the most significant authorisation is the Decree of Authorization and cost recognition system environmental compatibility, which is issued, based on the type of projects to be approved, by the MASE together with the Ministry of Culture (MiC) (part II of Legislative Decree no. 152/2006, those following the Environmental Impact Assessment procedure - national EIA) or the Region concerned (Annex III part II of the Legislative Decree no. 152/2006 which follow the regional EIA procedure). For some specific projects, provided for in Annex II-bis of the Legislative Decree No. 152/2006 (such as the construction of a new temporary depot), it is necessary to proceed to a prior verification of being subject to EIA[6].

Former Garigliano Nuclear Power Plant – Dismantling of Contaminated Stack

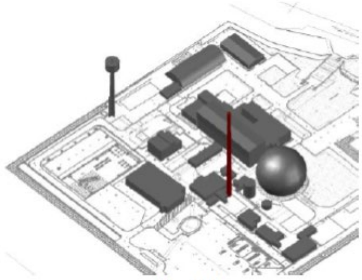
1st level of authorisation: Deactivation Decrees 2012

2nd level of Authorisation: 2013 after submission of RPP to ISIN

Status: completed (2017)

RRS application was part of the larger decontamination, monitoring and stack's demolition project:

- Developing of Robotic Equipment for remote decontamination (Figure A1.9)
- Developing of specific Tool to scarify the internal surface
- Developing of specific Tool to take concrete samples for characterisation purpose
- Mock-up (1/10 of height) construction for efficiency and reliability tests
- Scarifying and Characterisation activities of the GA Nuclear Power Plant Stack Internal Surface
- Wind Tunnel Tests for Stack Structural Analysis
- Top-down Breaking of fully decontaminated GA Nuclear Power Plant Stack Garigliano
- Construction of the new stack



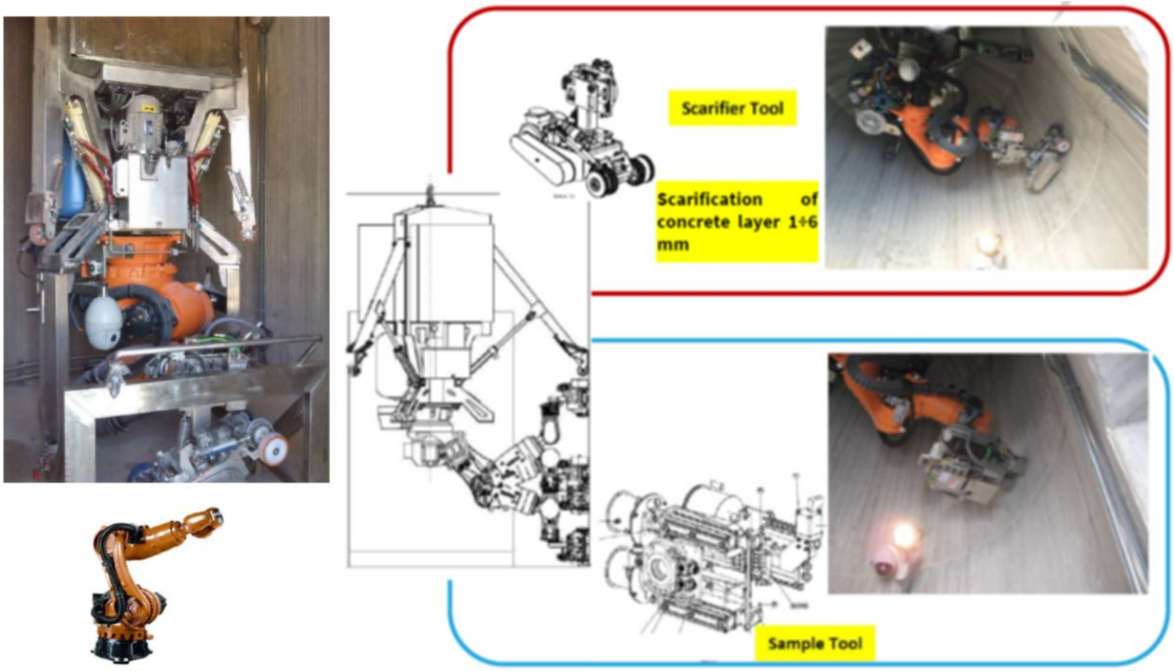
Garigliano
3D Model of GA NPP (Stack in red)

Garigliano
91 metres High of Reinforced Concrete Stack

collective meetings (so-called 'conferences') also aimed at issuing an administrative provision. It can be seen both as a procedural module for simplifying a procedure, and as a tool for coordinating the interests involved, in order to weigh and aggregate them. In the past, when the service conferences had not yet been established, it often happened that a proceeding got stuck due to the sequential nature of the request and obtaining of the authorisations by the individual bodies. With the law n. 241/1990 and the establishment of the Conference of Services, there has been an acceleration of the administrative procedures involving a plurality of administrations. The latter, in fact, meet "in a single location and on a single occasion" and decide within a single board. Also characteristic is the application of the "majority principle", according to which the various administrations concerned meet and vote for authorisation: a proceeding is not necessarily abandoned due to a single authorisation denied by a single administration, but the authorisation is granted on the basis of the majority of votes within the services conference.

[6] Further details are at: https://sogin.it/en/group/authorization-and-cost-recognition-system.html.

Figure A1.9. Robotic Equipment for remote decontamination with scarification and sampling tools



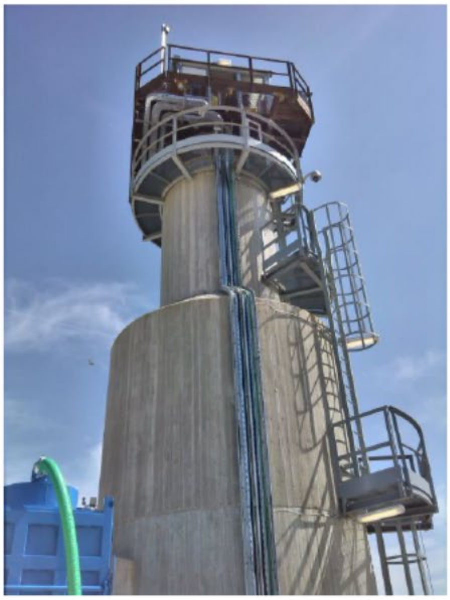
Note: Equipment was based on commercial robot arm (6 axis) installed on a load-bearing frame; it was suspended along the chimney by a safety cable. The equipment was equipped with position sensors, centreing and stabilisation mechanisms, power supply and functional tools.

Figure A1.10. Robotic decontamination and characterisation activities

Robotic Decontamination and Chracterizatoion Activities	
Scarifying Purpose:	Remove a contamination layer from the internal surface to achieve radioactivity concentration below **Clearance Levels** (Bq/gr – Bq/cm²)
Concrete Sampling/Chracterization Purpose:	Provide stack surface characterization data to determine the degree of **propagation of contaminants** through the interior concrete wall at different heights. Demonstrate in the **Final Characterization Campaign** that radioactivity concentrations are below clearance levels.

ISIN has provided various comments and observations on civil engineering matter and safety of demolition equipment (see figure A1.10) , HVAC, electro-instrumental etc., subsequently implemented both in the design and in the executive phase (e.g. request for a second scarifying treatment): ISIN was also present during the tests (FAT) on the robot's capabilities in the mock-up of the stack.

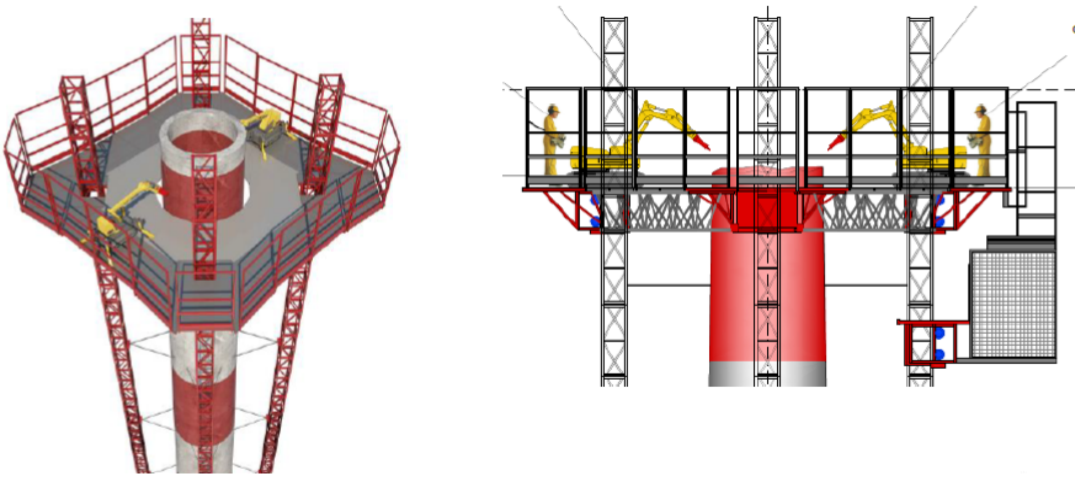
Figure A1.11. Mock-up of the stack for the facility acceptance test of the robot equipment



Mock-up of 12 metres high	
Purpose:	• Test of Robotic Equipment • Set-up of main Parameters
Tests of:	• Remote Control System • Concrete Scarifier Tool • Concrete Sample Tool

ISIN has not given any specific comment for the robotic part, neither observations nor prescriptions, except those of general safety, which are already suitably implemented in the project.

Figure A1.12. The demolition technique used after the decontamination of the stack



Former Latina Nuclear Power Plant – Cutting facility for dismantlement of large components

1st level of authorisation: Conference of service 2012

2nd level of authorisation: the RPP was submitted to ISIN in 2013 and approved in 2016

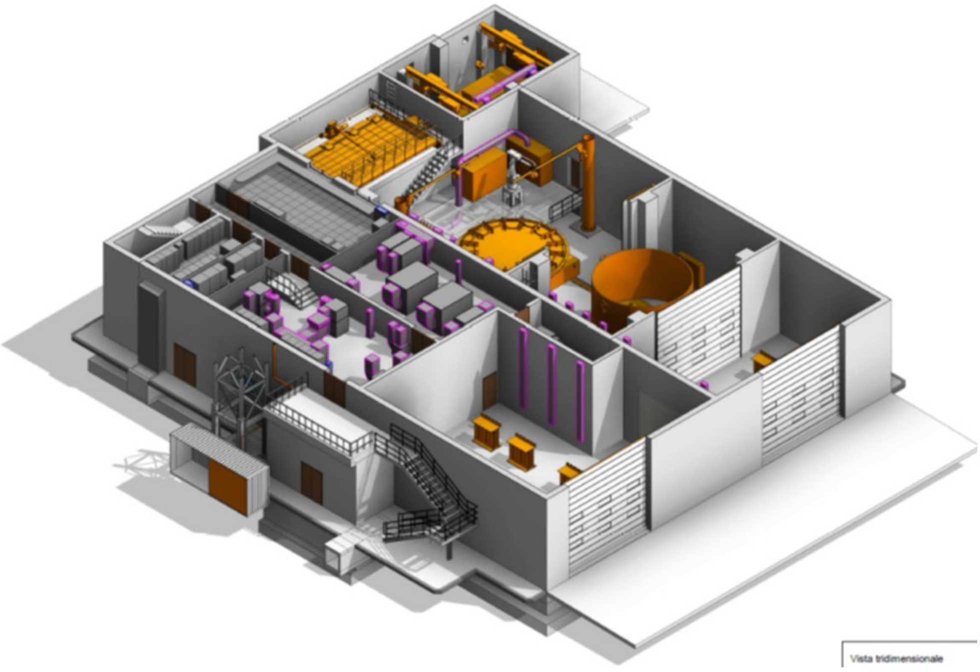
Status: Construction completed, SAT ongoing

Figure A1.13. The reactor building of former Latina Nuclear Power Plant, with 3 out of 6 steam generators

Figure A1.14. Steam generator (SG)

RRS application, also in this case, is part of a larger project. The main purpose of the facility (Figure A1.13) is to dismantle the sections (weight from about 30 t to 120 t each, thickness 55 mm) of n.6 SG-steam generators (about 600 tonnes each, Figure A1.11 and A1.12), maximising the recovery and reuse of the steel. The secondary purpose is to fragment any other large components resulting from the future decommissioning of the reactor building. Each section of the steam generator (SG) will be emptied of the internals (mainly tube bundles), will be segmented according to a special cutting plan into easily handled pieces, to allow mechanical (water jet and manual removal of any hot spots) and chemical (acids) decontamination.

Figure A1.15. Dismantling facility



The shell will be cut using a commercial 6-axis robot arm (Figure A1.16) equipped with an oxy-gas torch (acetylene fuel) which will make both longitudinal and circumferential cuts in semi-automatic mode (pre-set paths). The robot can also be operated directly and locally by an operator to make ad hoc cuts on more complex geometries (for example appendices external to the shell, nozzles, etc.).

Figure A1.16. 6 axis robot arm

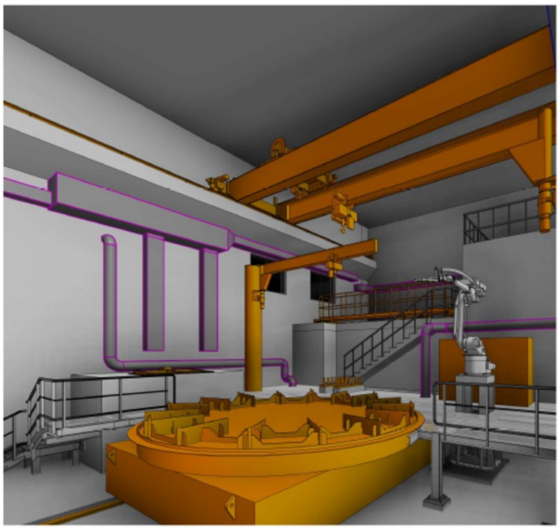


Figure A1.17. Workshop side-view

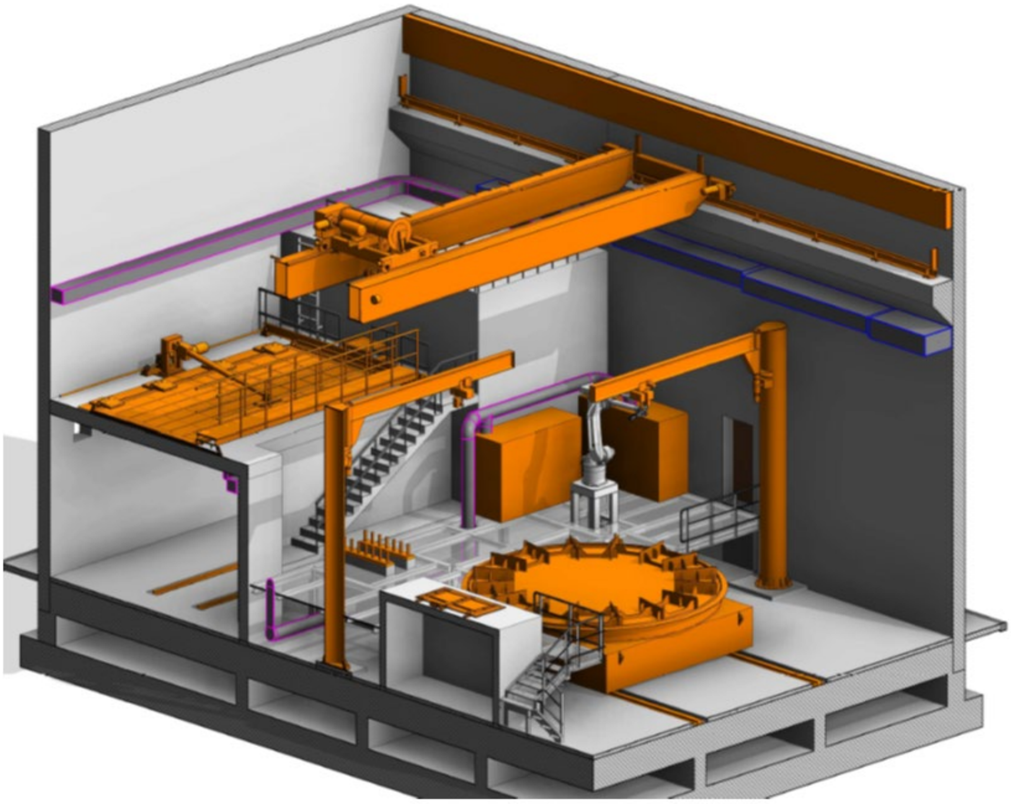
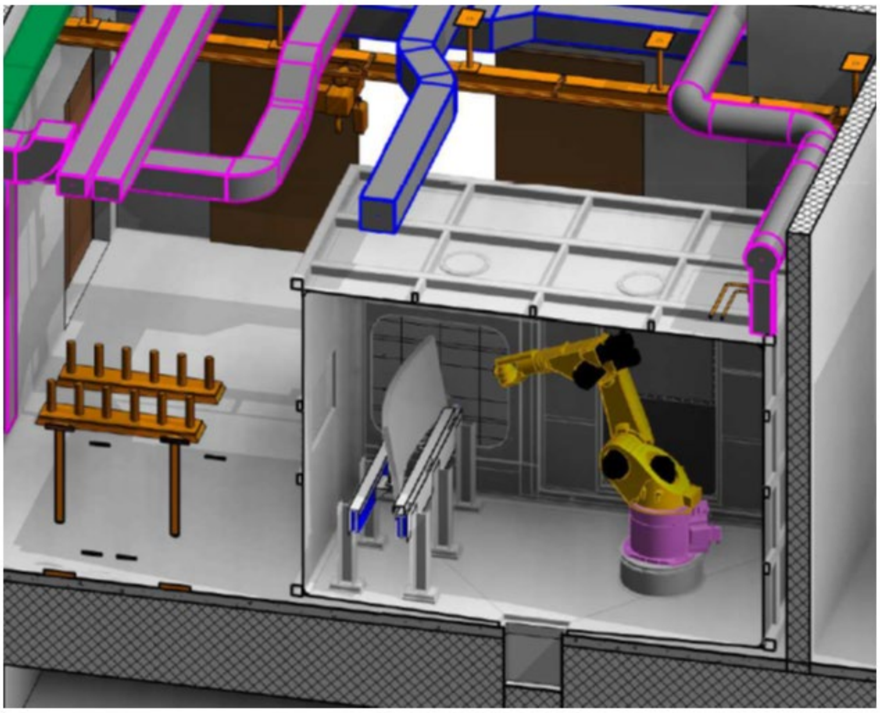


Figure A1.18. High-pressure water nozzle



The optimal distance of the torch from the surface being processed is guaranteed by a position sensor. A series of interlocks guarantees the safety of the operators inside the cutting workshop following movements of the robot or avoids collisions with other devices installed in the workshop (cranes, rotating platform, etc.). The SGs section enters the workshop via a rail trolley (Figure A1.17), equipped with a revolving platform whose movements are co-ordinated with the set cutting path.

With the aid of a second robot[7], the first decontamination will be carried out using a high-pressure water nozzle.

As in the case previously described ISIN has not given any specific comment for the robotic equipment, neither observations nor prescriptions, except those of general safety, already suitably implemented in the basic and in the building design.

A.6. Test case from Switzerland/Nuclear Regulator

Introduction

It is foreseen that some activities (emplacement of highly active waste or the emplacement of the backfill) in a geological repository will be carried out remotely. This test case aims to demonstrate the implementer-regulator interaction regarding the Swiss repository.

Legislative and regulatory background

The Nuclear Energy Ordinance stipulates in article 65 (Test areas) that before a deep geological repository may be put into operation, the technologies of relevance to safety

[7] Originally (in the basic design), the second robot had not been taken into consideration. Its introduction is due to an optimisation of the processes developed in the executive design phase.

must be tested and their functional capacity must be ascertained. This concerns in particular:

1. the emplacement of backfill material;
2. the removal of backfill material for the purpose of recovery of waste packages;
3. the method of recovery of waste packages.

The Swiss regulator ENSI added the following requirements in its guideline G03 "Geological Repositories":

7.2 Waste Emplacement

g. When carrying out construction, emplacement, backfilling, sealing or dismantling work at the same time, both operational and long-term safety have to be ensured.

7.3 Backfilling and Sealing

b. Backfilling and sealing of the emplacement caverns and drifts have to comply with long-term safety requirements. The seals have to have sufficient mechanical stability to protect the backfilled emplacement drifts and to withstand swelling and gas pressure in the emplacement drifts.

7.4.2 Concept for the Possible Retrieval of Radioactive Waste

1. The general licence application has to include a concept for the possible retrieval of radioactive waste. As a minimum requirement, the concept has to describe the planning, logistics, construction and monitoring steps required to ensure retrieval is possible up to the time at which the repository is closed.
2. The construction licence application has to include a more detailed concept for the possible retrieval of radioactive waste and a project for demonstrating the retrieval technology in the test areas.
3. The operating licence application has to include a concept for the possible retrieval of radioactive waste that has been updated based on the results in the test areas.
4. The concept for possible retrieval of radioactive waste has to be periodically updated during the operational phase and submitted to ENSI.

These legal and regulatory requirements are not of specific nature. They formulate aims, safety functions that have to be fulfilled. The implementer has to demonstrate that whatever procedures and technology is being used, fulfil these requirements to operational and long-term safety of a repository.

Research, development and demonstration programme of the implementer

The Swiss implementer Nagra publishes every five years its research, development and demonstration plan regarding the realisation of a geological repository.

https://nagra.ch/downloads/technical-report-ntb-21-02/

The RD&D Plan documents the objectives, scope, nature and timing of future RD&D activities and describes how existing open questions have been addressed. It outlines both a strategic plan for Nagra's RD&D activities contributing to the implementation of a combined repository or two separate repositories for high-level waste (HLW) and low- and intermediate-level waste (L/ILW) as well as a technical work programme consistent with the strategic objectives.

The specification, planning and implementation of RD&D is a needs-driven process, where the general drivers are the optimisation processes that must be carried out from the perspective of safety (recurring safety cases at each milestone) and implementation (confidence underpinning the feasibility of the design at each milestone). The ongoing development of the repository concept, design and components currently represents an important component of the RD&D activities.

In the report, the focus is on assessing and outlining the work required to further develop Nagra's science and engineering base and to ensure that the technology, data and expertise necessary for optimising the concepts and achieving future milestones in repository planning and development, including eventual implementation, are acquired in a timely and cost-effective manner. The scope of the report is thus wider than describing activities that are defined sensu stricto as RD&D.

As part of this optimisation process (safety, feasibility, implementation and thus also cost), this also includes the development of alternatives at all levels to ensure flexibility in terms of including future developments in the concepts. Much of the RD&D is necessary to contribute towards and underpin future decision making. While feasibility will be demonstrated at a conceptual level for the general licence applications, there are many areas of the programme where maintaining flexibility is highly beneficial. Such flexibility is particularly valuable in areas where considerable progress is expected in the intermediate term, e.g. specific technological developments and advances in materials science.

The Implementation Optimisation Roadmap is strongly linked to the Safety Optimisation Roadmap because relevant considerations in the optimisation of protection and safety measures are particularly relevant for implementation. These include the separation of mining and construction activities from waste emplacement activities, the use of remote handling equipment and shielded equipment for waste emplacement where necessary, the control of the working environment to reduce the potential for accidents and their potential consequences and minimising the need for maintenance in supervised and controlled areas. Contamination has to be controlled and prevented to the greatest extent possible (IAEA, 2011). A balance has to be struck between safety optimisation and the need for the project to be measured from an efficiency and economic point of view.

Aspects of remote handling and the development of the required technology is further described in the report:

Demonstration of emplacement, backfilling and retrievability of the HLW canister and L/ILW container (page 95).

Once the technology for emplacement and retrieval has been developed, it will be demonstrated that this can be realised safely and in accordance with the requirements on the subsurface environment. The demonstrations for each repository type can be combined into one experiment if this is considered advantageous. The actual demonstrations will be preceded by a detailed testing programme in surface laboratories, first of the individual components and then of the entire demonstration sequence to reduce the experimental risk underground.

For the HLW canister, the demonstration will include the emplacement of the pedestal with the canister and backfilling of the emplacement drift with granular bentonite material using remote handling if the current repository project is to be pursued. Retrieval will require the remote removal of the backfill material and the canister. Compliance with all requirements will be checked.

Design and technology development (page 99/100)

Surface-based activities

The final HLW canister design will be selected in anticipation of the construction licence. The materials and prototypes will be developed and tested at full scale. Further testing and optimisation of backfill materials, including their detailed specification, will also take place. However, the main principles and methods will have been established earlier. The backfilling technology will have to be designed for industrial application in a repository, involving a more robust design as well as further mechanisation of the backfilling process. The design will include a feeding device for buffer material supply in the emplacement drifts. Once the container design and the handling requirements are established, appropriate tools for container handling in the surface and underground facilities will be developed and tested.

The emplacement of the HLW canisters and the buffer emplacement in the repository will be further optimised based on new information, and alternatives will be evaluated as they become available. This will be based on remote handling due to radiological protection requirements.

In anticipation of the construction licences, Nagra will develop a closure concept for the repository. In order to demonstrate the technical feasibility of implementing reliable long-term seals, sealing structures have to be designed, built and tested by means of full-scale demonstration experiments under realistic conditions. Measures for temporary closure of the facility will be developed (feasibility of constructing temporary plugs with a performance of a few decades to a few centuries).

The bulk of the technological development and testing will take place in surface-based laboratories and possibly also generic underground research laboratories (e.g. Mont Terri Rock Laboratory) as this provides maximum flexibility. Only in the final phase will certain demonstrations on a 1:1 scale take place in the BEUU in anticipation of the submission of the operating licence applications.

A detailed design for the surface facilities with the encapsulation plant, including the necessary equipment and procedures, has to be in place in line with operational safety requirements for the construction licence.

For the construction and operating licences, other aspects also have to be considered, including security, and, for the HLW repository, the issue of safeguards. A concept for the preservation and transfer of information across generations as well as a concept for marking the disposal site will be developed.

Period from 2032 to L/ILW construction licence application (2040) (page 127)

During this period, similar activities will be started for the HLW emplacement and retrievability design and technical solution. These are expected to be more complex as remote handling is required.

Period from 2040 to granting of HLW operating licence (2060)

The HLW design will continue to be developed in parallel with the supporting technologies through internal work and international collaboration. Similarly to the L/ILW process, an HLW emplacement and retrievability solution will be established shortly before the submission of the HLW construction licence application, the HLW construction method will be fixed, and the plan for EUU demonstration experiments will be finalised.

In situ HLW emplacement and retrievability demonstration experiments will be carried out to verify every aspect of the emplacement and retrievability solution leading into the submission of the HLW operating licence application, thus concluding the RD&D for emplacement and retrievability of HLW.

Planned RD&D in the next five to ten years (page 188)

The main activities for the generic design concepts are engineering development and advancement of technical methods for planning and operation of deep geological repositories. Digitalisation offers many new possibilities, which will be investigated in more detail in the years leading up to the general licence applications and beyond. In anticipation of the general licence applications, the conceptual design for the retrieval of the waste will be further detailed. Special focus for the operational planning will be on in-repository transport (autonomous vehicles) and remote handling (for transport, emplacement equipment and retrieval). Here, the exchange of experience with other waste management organisations will also play a key role.

Planned RD&D in the next five to ten years (page 196)

The successful emplacement of the buffer in the FE and HotBENT experiments demonstrates a good level of readiness regarding emplacement technology. No further activities are foreseen for the general licence applications, apart from small refinements to the current methods.

After the submission of the general licence applications, further development of the backfilling technology, including remote handling, will take place as a basis for the submission of the construction

licence applications. In this context, the prototype buffer emplacement machine will be further developed to an industry-standard tool, with reliability, efficiency and complexity optimised for day-to-day application.

Summary

With regards to the Swiss repository, the implementer plans its development activity for remote handling (for transport, emplacement equipment and retrieval) to take place in the 30s and 40s. Hence, there exist no current need for the implementer to enter a discussion with the regulator to revise regulation for the foreseeable future.

On the regulator's side there is also no need to address the issue now, since its requirements are oriented towards safety functions, or in a general way goal oriented. Using current regulation, an implementer will develop the technology need for the remote handling purposes and in preparation of doing so will enter a dialogue with the regulator to ensure that this development will fulfil any regulatory requirement.

A.7. Test case from the United Kingdom/Nuclear Regulator (1)

Who was interviewed

David Smeatham, Head of Innovation, Office for Nuclear Regulation

Description of the project

Setting up an innovation hub within the United Kingdom's nuclear regulator, the Office for Nuclear Regulation (ONR), to help enable the proportionate regulation of innovation in the nuclear sector where it is in the interest of society and beneficial to the industry's safety and security. Our approach to regulating innovation includes providing advice to licensees, dutyholders and requesting parties, and their supply chains, on potential innovations for application in the nuclear sector.

We have been piloting this approach over the last year. This pilot has included the development of a regulatory sandbox that allows industry, academics and regulators to engage in a safe space to discuss potential applications of innovation. This includes the use of artificial intelligence to assist the operation of robotic solutions with the potential for this to lead to autonomous operation.

Challenges/learning from the permissioning (or foreseen if in the future)

The innovation hub engagement is early in the technology readiness scale and is focused in the development of relevant good practice to provide a framework to allow regulatory decisions to be made. It is however recognised that innovation at higher technology readiness but were relevant good practice does not exist, then early engagement with regulators can be very beneficial. The innovation hub can help support this engagement. But, it is not a substitute for robust regulation. ONR continue to apply the same level of scrutiny to its regulatory decisions – in the future some of the regulatory benchmarks used could be based on the work of the innovation hub.

Any other recommendation from this perspective

The innovation hub aims to provide a safe space to allow industry and the regulators to develop relevant good practice. Arrangements are in place to make sure this engagement does not impact on our independence as a regulator. However, the innovation hub has a knowledge management and dissemination strategy to ensure any lessons learnt and consideration of relevant good practice are fed into future regulatory decisions where appropriate.

This work is also supported by horizon scanning activities to help make sure any future regulatory decisions are supported by relevant good practice.

A.8. Test case from the France/EDF

Who was interviewed

Reporting by Emmanuel Wozniak (EDF Decommissioning and waste management unit, robotics' team manager), interview of technical directors of decommissioning projects.

Description of the project

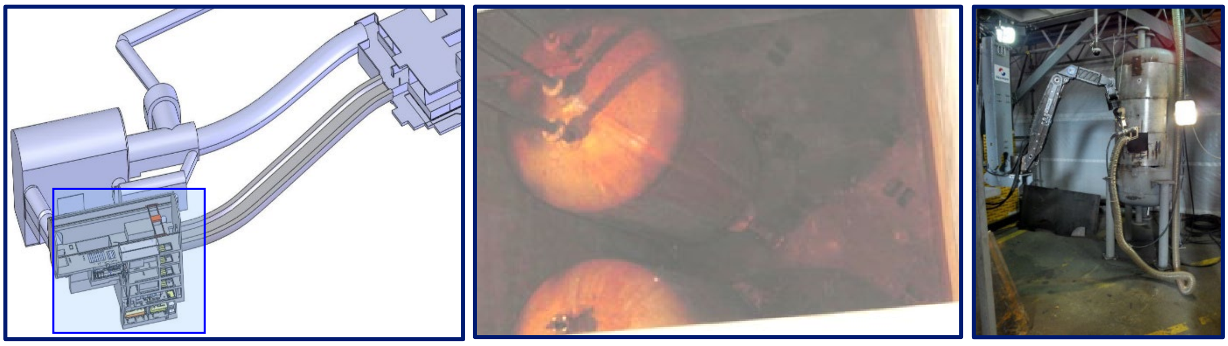
Tanks dismantling

Tank dismantling in rooms with difficult accessibilities and high ambient dose rate, which does not allow human activities during a long time.

Use of a remote-controlled 6 axis arm (Kraft PREDATOR) with several tools such as plasma torch, shears or disc saw.

Operations fully done in teleoperation from a remote-controlled room with two operators: one for arm control and one for monitoring.

Figure A1.19. Remote-controlled 6-axis arm with tools



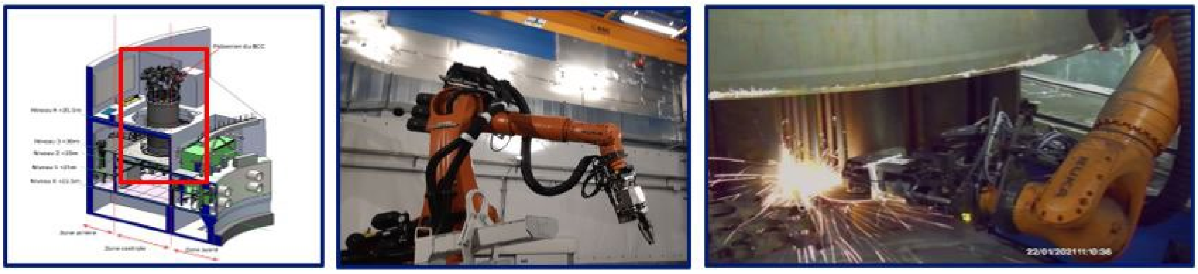
Equipment dismantling

Very high dose rated component dismantling, with potential sodium presence and a complex geometry.

Use of a robust manufacturing arm (KUKA KR 360 FORTEC) with numerous tools such as shears, circular saw or grippers.

Operations realised both thanks to automated positioning and teleoperation from a remote-controlled room with two operators: one for arm and axis control and one for monitoring.

Figure A1.20. Manufacturing arm with tools



Stage in the development (initial research at university level up to ready for deployment – incl. technology review level/TRL)

For both of these projects, EDF approach was to use on commercial shelf equipment in order to take advantage of previous feedbacks from other industries.

Safety function (or not)

Safety functions placed on other equipment as a result of the use of robotics

Robotic equipment was not identified as safety function. However, safety concerns integration had been taken into account during all the dismantling process:

- Intervention scenario studies.
- Equipment conception and qualification.
- Equipment use, maintenance and recovery procedures.

- Operators training.

Safety/ radiological consequence of spurious operation

Safety/ radiological consequence of fault operation – not doing something it should

Dismantling operations has been performed on equipment disconnected from usual networks: for Chooz, tanks were isolated from all the network, and for Creys-Malville the equipment had been transferred in a dedicated cutting room.

Challenges/learning from the permissioning (or foreseen if in the future)

Timing of engagement with reg

Based on complexity, maturity, uncertainty, safety significance, consequences

Different possible stages

Optioneering vs concept design vs detail design

Technical challenges

- Novelty/complexity of more extreme /innovative applications (e.g. from universities)
- Design processes employed/systematic approach, including supporting evidence

Challenging areas in the submission supporting permissioning (cybersecurity, engineering substantiation, maintainability, fault recovery, secondary waste and sustainability)

Availability of suitable standards/designed or certified against applicable standards

Uncertainty in reg expectation

Human factors considerations, including SQEP operators/supervisors

Regulator point of view was to assure operators protection from radioactive exposition, therefore the use of remote-controlled equipment was fully accepted and recommended for these activities.

During hazards associated with robotics equipment (long duration maintenance, breakdown), regulators' approach has been to favour operators' protection and to encourage to continue dismantling operations using remotely operated equipment instead of continuing operations with more traditional manual cutting operations.

Any other recommendation from this perspective

NA

Any areas of improvement – blockers

- Reg independence vs reg uncertainty

- Eng substantiation vs functional hazard assessment
- Balance of risk and ALARP arguments

Any other recommendation – enablers

- Staged permissioning (“banking” of decisions)
- Demo/prototyping/mock-up
- Expert panel/sandboxing
- Questions
  - How to upskill in an efficient way and identify areas where upskilling is required
  - How to raise awareness of future applications in R&D
  - How to raise awareness of future requirements for R&D

Good practices regarding regulators acceptance :

- Use of on commercial shelf equipment to improve reliability and benefit from feedback.
- Studies and tests of recovery operations to perform.
- Operators training to be well prepared and done throughout all along the projects duration (very long duration, skill not commonly found) on both virtual environment (including during design studies to optimise equipment conception) and representative mock-up (before and during operation if new operators have to be trained).
- Consider the robotic device and all other components as a unique piece of equipment to use the correct tools/supports for proper operation (for example, the occurrence of a breakdown due to the use of cutting tools incompatible with the robotics’ use calls into question all of the remotely operated equipment).

Recommendations/improvement to favour regulators acceptance:

- Ensure that the selected intervention scenario is studied in accordance with the robotic equipment used and not limited to considering the simple replacement of the operator by a robot in a classic scenario from early beginning (response to the call for tenders) and through all studies process (including a re-interrogation during any scenario modification).
- Develop and qualify reliable technological bricks to be able to automate tasks instead of performing them remotely (virtual serving, AI assistance, …), in order to use human competencies at their best (monitoring, breaking avoidances, …).
- Consolidate the dismantling times estimated during the studies so as not to underestimate them at the risk of causing the regulators to lose confidence in our mastery of the implementation of remotely controlled operations (and therefore of questioning the reliability of this equipment).

A.9. Test case from the United Kingdom/University of Birmingham

Test case: semi-autonomous robotic laser cutting for size reduction

Who was interviewed

Professor Rustam Stolkin, Chair of Robotics, University of Birmingham, United Kingdom.

Led the University of Birmingham team via his consultancy A.R.M Robotics Ltd, in collaboration with UK National Nuclear Lab Ltd.

The University of Birmingham team developed the algorithms and software to achieve autonomous motion planning, guided by 3D computer vision, to enable a robot arm to deliver a 6 kW laser on a cutting trajectory over contaminated waste objects with arbitrary surface shapes.

The NNL team developed the robot demonstrators, including designing and constructing cells, physical installation of robots and tooling, and handled nuclear-specific issues of safety, hepa-filtering, etc.

Perspective of interviewee: robotics technology developer.

Description of the project

The United Kingdom is the location of many contaminated objects and materials which will need to be size-reduced. One example is hundreds of severely degraded, deformed, and contaminated steel “skips” which have been containing spent fuel rods in storage ponds for many decades.

UK NNL Ltd envisions a plant in which such objects can be brought into a cell, and then cut into pieces using a laser mounted on a robot arm. The pieces can then be placed into containers for long-term storage. However, the steel skips may be significantly damaged and deformed compared to the original CAD models. Furthermore, the shape of these objects will change progressively during cutting.

It would be extremely painstaking to programme by hand each movement of the laser cutter. Furthermore, this would require air-fed suit entries of humans into the cell. Teleoperation is difficult because the tip of the laser must maintain the correct stand-off distance of around 1 cm (if the laser tip collides with the surface it will be damaged); the laser axis must be maintained orthogonal to local surface curvatures; and the laser must move over the cut surface with a specified cutting feed rate.

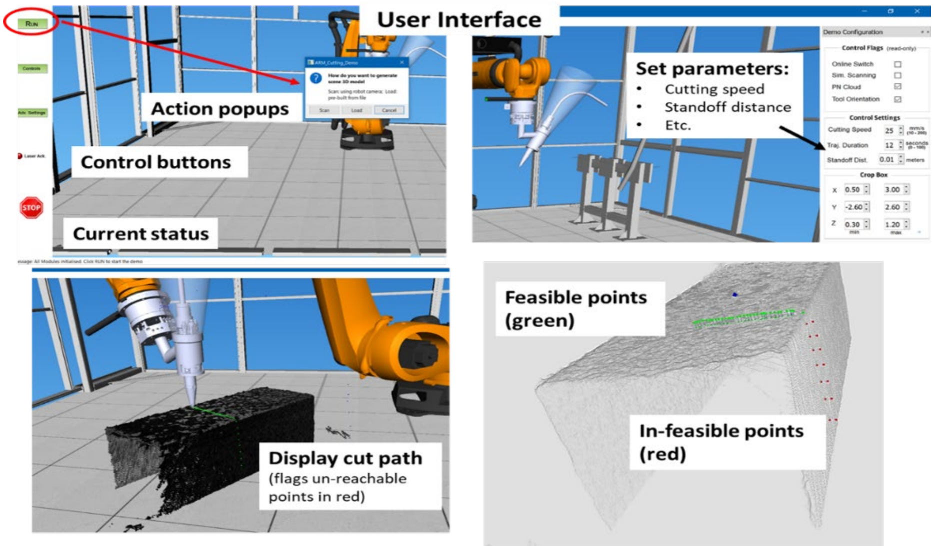
Figure A1.21. Empty nuclear fuel skips in the first-generation Magnox storage pond. Image courtesy of Sellafield Ltd (in public domain)

Type of solution/technology (fully automated/autonomous, supervised, teleoperated)

We have developed a semi-autonomous solution (see Figure 39 to Figure 43), which can be applied to the above steel skip challenge, and more generally to many other applications where remote robotic cutting is needed of hazardous materials and objects inside hazardous environments.

- The robot first picks up a 3D imaging device (point cloud camera) using an automatic tool changer interface.
- The camera is moved to several different viewpoints.
- The partial point clouds from each view are automatically fused to create a scene model (Figure A1.23).
- The work-piece (object to be cut) is automatically segmented from the background scene. This work-piece is then displayed on a user interface as a virtual work-piece relative to a virtual robot (Figure A1.23)
- The human user then selects a cut path by making two mouse clicks to indicate start and end positions of the cut.
- The software then: i) automatically plans a cut path on the work-piece surface; ii) plans the path of the laser to maintain correct stand-off distance and orientation; iii) plans the trajectory of all robot arm joints to deliver the laser along correct trajectory, maintaining correct feed rate, while avoiding collisions between all robot parts and the surrounding scene (which can be loaded from a CAD file and/or created via computer vision).
- Our interface then shows a virtual robot performing a virtual cut on the virtual work-piece (Figure A1.20). The human operator can then approve the cut if it looks correct.
- The robot then puts down the camera and picks up the laser head using the automatic tool changer system.
- The robot performs the real cut on real work-piece (Figure A1.22 in inactive demonstrator 2022, Figure A1.24 in live radioactive hot cell 2017).
- The virtual environment can be run in real time, synchronised with real robot, as a digital twin. This provides additional situational awareness in conjunction with conventional CCTV camera views. The virtual view can be rotated to arbitrary viewpoints during cutting (Figure A1.24).

Figure A1.22. Human-robot interface and digital twin environment, of latest version demonstrated in July 2022.



Note: The robot acquires a 3D model of the waste work-piece using eye-in-hand imaging. A cut path is planned automatically based on user-indicated start and stop locations. Feasible and in-feasible cut paths are indicated to the user

Figure A1.23. The virtual robot demonstrates a virtual cut on the virtual work-piece before final approval to execute a real cut

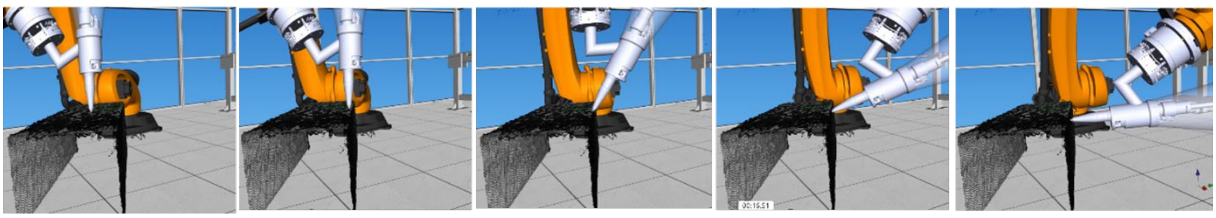


Figure A1.24. Enhancing situational awareness with real-time digital twins in laser cutting operations

The real-time digital twin provides significant additional situational awareness during the real laser cutting operation, in addition to traditional CCTV cameras which have limited views.

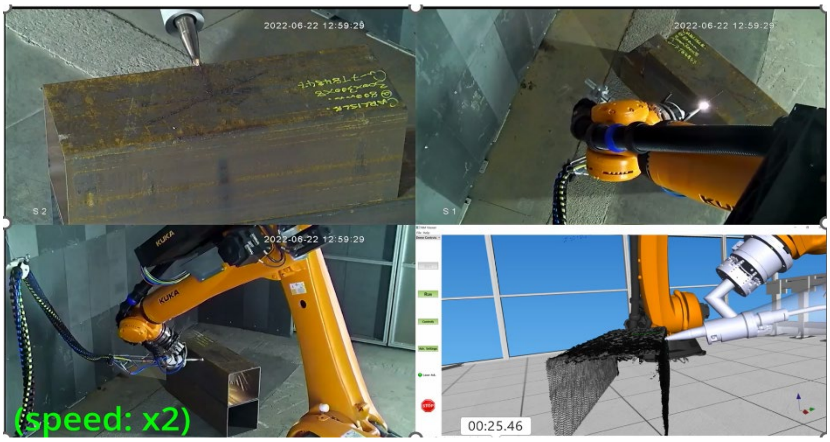
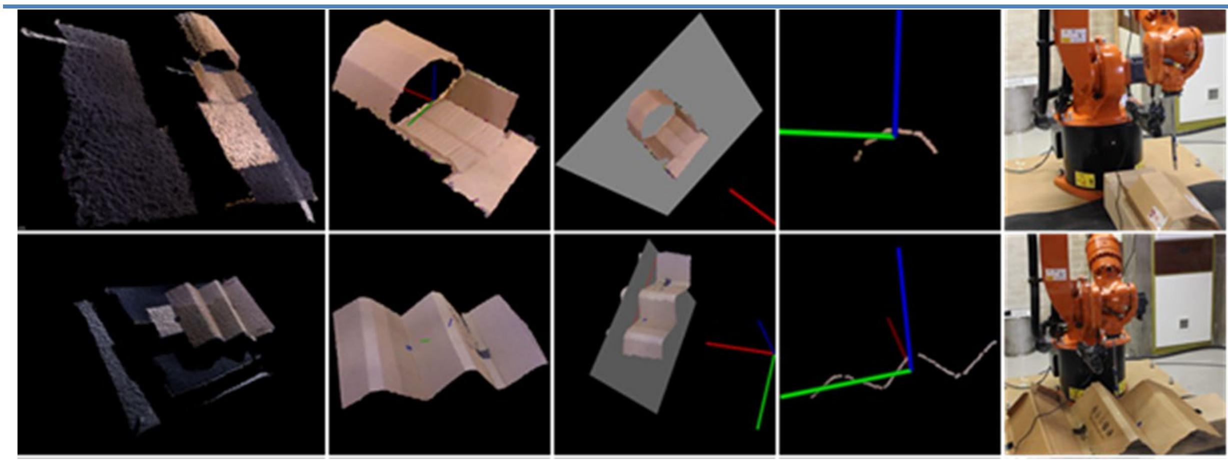


Figure A1.25. In-lab testing of first prototype 2016-2017 courtesy of Prof. Stolkin, University of Birmingham, United Kingdom)

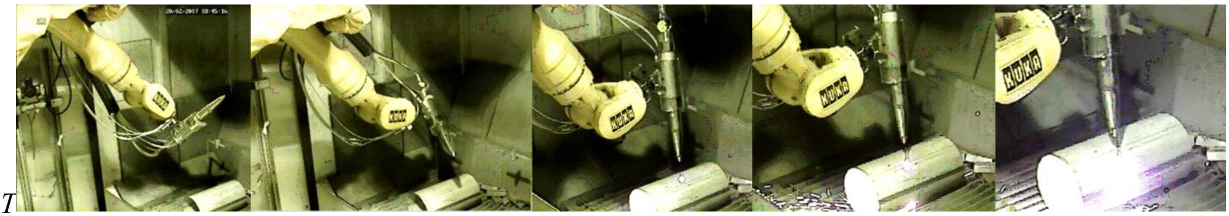


a)	b)	c)	d)	e)

a) The robot moves the camera to multiple viewpoints, and reconstructs 3D model of the scene.
b) The AI automatically segments the foreground work-piece from background points.
c) The human operator selects a cutting plane using two mouse clicks.
d) The AI automatically selects the points along the surface to be cut, and plans a trajectory for the laser, including desired laser stand-off distance and automatically maintaining laser axis orthogonal to the local surface curvature throughout.
e) The AI automatically plans a collision-free trajectory of the robot's joints to deliver the laser along the cutting trajectory

Explanatory demo video: www.dropbox.com/s/4tkyte1uu2nt25o/LaserCutting.wmv?dl=0

Figure A1.26. World's first autonomous robotic arm in a radioactive environment for laser cutting: ARM Ltd's AI-controlled operation of robotic laser cutting of curved steel surface in a real radioactive hot cell at NNL, Springfields Nuclear Site, United Kingdom, 2017



Images courtesy of UK National Nuclear Lab Ltd. (in public domain).
Full video available at:
https://www.dropbox.com/pri/get/proposals/SBRI%20InnovateUK/PrestonLaserCut.wmv?_subject_uid=66563199&w=AAAmD3hAZ0UO5I-mbEBg_szhNBLejAWQE9ll9xF-fJpsPQ

Stage in the development

This has been demonstrated in a live radioactive environment, cutting contaminated metal in a hot cell at the UK Springfields nuclear site in 2017. The UK Nuclear Decommissioning Authority regards deployments in active environments as TRL9. However, we consider our work to be a convincing R&D demonstration at more like TRL7 or "TRL7+".

Safety functionalities

Our system demonstrates a number of safety functionalities:

1. This system minimises the need for human workers to enter and work inside the hazardous zone.
2. Our algorithms automatically plan collision-free trajectories.
3. The software will detect unreachable positions, and highlight cuts that are unreachable without collisions, so that operator can suggest an alternative cut.
4. A virtual cut is performed by a virtual robot, so that a human expert can inspect the proposed cutting motion and approve it, prior to the real cutting operation being executed.
5. The digital twin provides enhanced situational awareness during cutting.
6. If the work-piece/scene changes, the scene can be re-imaged to create a new 3D model (imaging and model generation can be performed in seconds automatically).
7. The cut can be terminated at any time with an emergency stop button, and the robot can then automatically return to the home position.
8. Our system could readily be combined with an additional layered system of additional lower level collision detection systems (e.g. range sensor, and force-contact sensors) to enable the robot to more rapidly and intelligently react to deforming surfaces in real time as the work-piece is progressively cut and dismantled.

Safety functions placed on other equipment as a result of the use of robotics

N/A

Safety - radiological consequence of spurious operation

Spurious actions would lead to two main consequences: i) the robot and tooling physically collides with the cell walls, or critical cell infrastructure; ii) the laser is directed at e.g. the cell wall or some critical infrastructure inside the cell. A separate, and important, safety consideration is that of the fumes created by laser cutting of contaminated metal work-pieces, with respect to hepa-filters.

Our first demonstration in 2017, at Springfields nuclear site in the United Kingdom, was developed in an active hot cell, cutting contaminated material. In this demonstrator, the cell walls were made of concrete. The key mitigations of risk were:

1. A human operator must hold a "dead-man's handle" type safety switch throughout the robot motion.
2. The cell walls are made of concrete, which is physically much stronger than the robot arm (20 kg payload KUKA KR20) with respect to impacts.
3. The laser did demonstrate some capability to cut concrete. However, the designed considered that, in worst case, it would take significant time to cut the thick cell wall, and the dead-man's handle and e-stop button were an acceptable mitigation.

In 2017, our early version of this system did display the cutting trajectory of the laser over the work-piece surface prior to real cut execution. However, we had not yet implemented a full digital twin virtual environment, which could have further mitigated collision risks by displaying the full robot motion to the human operator prior to cutting.

This additional safety step, as well as real-time digital twin for enhanced situational awareness during cutting, and an enhanced user interface, was developed and implemented for our second demonstration of these technologies in 2022.

Our second demonstration in 2022 was in an inactive demonstrator established at UK National Nuclear Lab's Workington facility. Here the cell walls were made of laser-proof panel material, and this laser-proof cell was housed in a larger concrete and steel enclosed zone.

The laser does generate some smoke/vapour. However, extensive tests of hepa-filters have been undertaken with positive results by NNL Ltd, using the active demonstrator at Springfields. NNL's safety study, including investigation of fumes and heap-filtering is reported here on IAEA's International Nuclear Information System (INIS):

https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=49098104

Safety/ radiological consequence of faulty operation

If a cut fails, e.g. the laser malfunctions, or a comms/network delay (between external PC running advanced motion planning code, and the industrial control cabinet of the robot) causes the robot to freeze, then the robot will return to its home position and the cut can be repeated or an alternative cut can be planned. All materials are safely contained within the hot cell.

Challenges/learning from the permissioning (or foreseen if in the future)

An important and positive learning from this is that it is possible, and has already been demonstrated, that advanced autonomous robotics technologies can progress (quite rapidly) compared to standards/regulation.

This is contrary to the expectations of many people in the industry. For our first demonstration, we commenced work on this project in late 2016, and developed the first software version from scratch in two months. The system was deployed in an active hot cell by early 2017.

Timing of engagement with reg

I am uncertain exactly of the engagement with regulators to enable this work, as it was handled by the NNL team, while my team handled the advanced robotics and computer vision.

My team were called in to solve the advanced robotics challenges near to the end of the three years LaserSnake2 project. Therefore the development, commissioning and regulatory approval of the laser cutting hot cell was achieved within that window.

NNL has carried out another project, where the robot was pre-programmed by hand, point by point – this was done using an inactive demonstrator, so that programming could be done by human operators standing next to the robot.

Other teams have attempted laser cutting by direct teleoperation.

Other work in the United Kingdom has used one company to capture scans and assemble a 3D work-piece model offline. This model has then been sent to a second company which performed robot programming, point by point using the 3D CAD model. This robot trajectory code was then sent back to the end user and installed onto the robot.

In contrast our system images the work-piece in a few seconds, and automatically generates the model in a few milliseconds. Once the human has indicated start and end points, the cutting trajectory is automatically computed in a fraction of a second. Our 3D models achieve mm or sub-mm scale accuracy using an off-the-shelf imaging device which is available for around EUR 7 000.

Technical challenges

This work relies on mathematically complex algorithms for: camera calibration; image registration; point cloud processing and smoothing and outlier removal; image segmentation; computational geometry; autonomous 6-dof (or 7-dof) motion planning; collision detection/avoidance during path exploration; hard-real time constraints for trajectory planning to ensure specified feed rate, and real-time comms between the motion planning software and the industrial robot controller. We have not seen this work repeated elsewhere worldwide currently at date of writing.

- Challenging areas in the submission supporting permissioning (cybersecurity, engineering substantiation, maintainability, fault recovery, secondary waste and sustainability)
- Uncertainty in regulatory expectation

Availability of standards and uncertainty in regulatory expectation

My understanding is that there are not yet specific regulatory standards available for autonomous functionalities such as autonomous motion planning based on scenes captured by computer vision.

However, it was possible to progress this system through regulation based on bounding constraints, such as cell walls being stronger than the robot, and resistant to the laser. I.e. advanced software could be regarded as a black box, within a robust system of fail-safes.

Human factors considerations, including SQEP operators/supervisors

There are significant challenges in the UK nuclear industry in terms of SQUEP. Full understanding of this technology (or even the ability to install the software and external libraries and dependencies and link to all interfaced devices) requires extremely deep expertise (at least upper end of post-doctoral). Therefore, it is necessary for expert robotics researchers to install, calibrate, test and operate the system on robot demonstrators that have been physically assembled by industry workers.

However, we have developed an increasingly intuitive front-end user interface, so this is now at the stage where our experts could install it, and train nuclear workers to operate it without our presence. *A live demonstration to the LaserSnake2 funding agency (Innovate-UK) was performed in 2017 by a nuclear engineer who my team had instructed how to run the system on his own.*

Any other recommendation from this perspective

NA

Areas of improvement

In our collaborative work with NNL Ltd, in 2016-2017 and again in 2022, my robotics team and I had no direct contact with regulators (Office of Nuclear Regulation, United Kingdom). Instead, this was handled by NNL project managers and nuclear engineers. These people have considerable experience and expertise in working with regulators, but do not have extensive robotics expertise.

In my opinion it would be *advisable for the robotics experts to be part of the conversation with the regulators*. I am uncertain as to how clearly the regulators understood the autonomous functionalities being deployed.

Engineering substantiation versus functional hazard assessment

I view the hazards breaking down as follows:

A robot arm, connected to advanced motion planning software, might move in unexpected ways. Such robot arms engender hazards in terms of unwanted collisions. which must be accepted, understood and mitigated by the end-user. In the event of collision with humans, hazard can be up-to-and-including danger of death.

1. Powerful lasers engender various obvious significant hazards which must be accepted and mitigated by the end-user. These hazards are fundamentally “cutting the wrong thing” – which might be a human, a piece of critical cell infrastructure or cell furniture, cutting open a container filled with a high-level contaminant, or cutting the cell walls.
2. When a laser is combined with a robot arm, coupled with autonomous motion planning, these risks (and any uncertainties) may be compounded.

3. When we place a laser on a robot arm, with advanced software, inside a nuclear facility, interacting with active materials, the risks and uncertainties further compound.

On the contrary, I believe it was possible to satisfy the regulators, by applying good engineering practices engineering which can acceptably contain or constrain all of the above eventualities.

Balance of risk and ALARP arguments

In my opinion the risks were adequately mitigated, and there is a clear case for overall benefits in terms of ALARP for human decommissioning workers.

Other recommendations

My impression is that this project passed through regulation quite fast and with surprisingly little difficulties. I am not certain if we should expect this in general for similar deployments of robotic systems controlled in adaptive ways by advanced software, including autonomous motion planning. Perhaps this case was an exception rather than the rule. I am also uncertain as to how clearly the regulators understood the extent to which the motion planning and control was autonomous. At the time we delivered the original 2017 demo, we had not yet completed the digital twin, so that the virtual robot motion was not displayed to the operator prior to live cutting, in the way that we can now do with our more recent versions (as described above).

Questions

How to upskill in an efficient way and identify areas where upskilling is required

This is a serious problem in my opinion. The industry (at least in some countries) generally still lacks people with the very deep expertise that is needed to fully understand such systems, or to develop, implement or maintain such systems.

How to raise awareness of future applications in R&D

I think that it is clear that this type of technology could be significantly disruptive and game changing for the nuclear industry. However, it has still been very difficult to gain traction and support for developing this technology further, despite successful (and widely known) high-TRL demonstrations.

How to raise awareness of future requirements for R&D

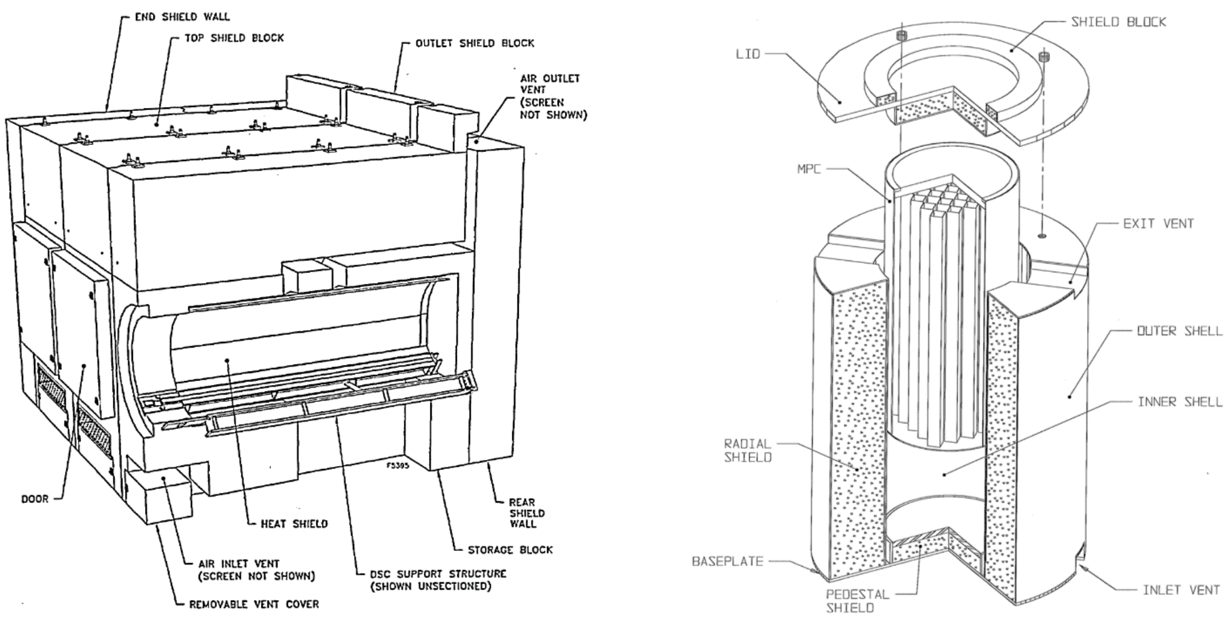
There are a number of additional technologies that I believe should be developed and integrated with the above system. These include sensors to enable real-time reactive behaviours to avoid collisions with moving or changing (e.g. springing out or collapsing in) of the cut surface during cutting. We have also proposed ways to incorporate AI-assisted teleoperation in which software ensures that stand-off distance, tool alignment and feed rate are maintained during human-steered cutting operations. My team are now seeking independent research funding to support these developments in the future.

A.10. Test Case from United States/US Nuclear Regulatory Commission

Storage of spent nuclear fuel

Nuclear Power Plants in the United States currently store spent nuclear fuel (SNF) on-site until an interim or long-term storage solution is developed. Following an appropriate cooling time, SNF is removed from the spent fuel pool and loaded into canisters for storage. The canisters are loaded into storage modules or overpacks, which provide an additional boundary to the environment for radionuclides within the fuel. Together these components are termed Dry Storage Systems (DSSs). These storage systems are typically used to store SNF on the site of the nuclear power plants and placed in Canister Independent Spent Fuel Storage Installations (ISFSIs). Heat is transferred from the SNF to the surface of the canisters and then to the environment through natural circulation. Air is drawn through vents into an annular ring between the canisters and the DSS shielding cavity to maintain cooling of the spent fuel.

Figure A1.27. Advanced NUHOMS System Horizontal Storage Module [1] (left) and HI-STORM 100 OVERPACK (right) [2].



Regulatory driver

The US Nuclear Regulatory Commission (NRC) requires that SNF in storage to be licensed under Title 10 of the *Code of Federal Regulation* (10 CFR) Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste." Licences for specific ISFSIs or certificates of compliance (CoCs) for DSSs have been issued for initial terms of 20 years. [2] During the initial licensing period, inspections may involve the external inspection of vents to ensure they are clear of obstructions, check for damage to painted surfaces to prevent corrosion, etc.

These licences/certifications can be renewed for up to an additional 40 years. [3] A licensee must submit an application to renew a licence to the NRC at least 2 years before the expiration of the licence in accordance with the requirements of 10 CFR 72.42(b). To renew a CoC, a certificate holder must submit a renewal application at least 30 days before the expiration of the CoC in accordance with the requirements of 10 CFR 72.240(b).

The NRC has developed guidance identifying ageing mechanisms that may affect DSSs following the initial licensing period during the period of extended operation. As part of the renewal application, licensees must demonstrate that structures, systems, and components (SSCs) important to safety will continue to perform their intended functions for the requested period of extended operation. An ageing management review (AMR) is performed to assess the proposed ageing management activities (AMAs). It addresses ageing mechanisms and effects that could adversely affect the ability of the SSC to perform their intended functions during the period of extended operation. This is achieved by identifying materials and environments of the SSCs (and their associated subcomponents), identifying ageing mechanisms and effects requiring management, identifying time-limited ageing analyses (TLAAs) and ageing management programmes (AMPs) for managing the effects of ageing. The NRC provides a Standard Review Plan (SRP), NUREG-1927 [4], that defines acceptable methods for the NRC staff to review and determine if the applicant has demonstrated that the specific-licensed ISFSI or the certified DSS will continue to meet the applicable regulatory requirements of 10 CFR Part 72 during the period of extended operation. A licensee may propose alternative means of satisfying the appropriate regulatory requirements; however, deviation from this guidance in whole or part may result in an extended NRC staff review schedule. [4]

Description of use case

An application of robotics and remote examination is the examination of DSSs for wear or corrosion products that may need to be addressed during the extended licensing period. When reviewing licence renewal application, the NRC staff may consider applicable consensus codes and standards. [4] Remote visual inspections are considered in ASME Section XI, Article IWA-2200, as a substitute for direct examination if the procedure is demonstrated to be capable of resolving characters and colours to a specified limit.

Efforts have been underway to develop technologies to support remote examination of DCSSs (dry cask storage system). The Electric Power Research Institute (EPRI) has generated a report that outlines various research projects related to the use of robotics to support the inspection of DSSs. [5] This report includes discussions of visual inspections as well as nondestructive evaluations (NDE). Included in Ref. [5] is an outline of several concerns that need to be addressed to deploy robotic tools for DSS inspection activities. These include:

1. Foreign Material Exclusion – The robotic solution should not introduce a foreign material into the inspection area which potentially adversely affect the performance of the DCSS.
2. Chemical Interaction – The robotic solution should not introduce chemical species which may result in adverse reactions with DCSS components.
3. Material Degradation – The robotic solution should be able to perform its intended function without measurable degradation due to the operating environment in which the solution is functioning.
4. Access limitations – The robotic solution should be able to successfully enter and exit the DSS, and traverse or bypass obstructions.

5. Radiation protection – The robotic solution should not increase ALARA considerations regarding radiation dose to workers or spreading of potential contamination.
6. Licensing – The robotic solution must be consistent with the licensing basis.
7. Operation – The robotic solution should allow the DSS to be quickly return to normal operation.
8. Other – False positive rate, inspection time, etc.

Testing of the robotics solutions developed included the creation of mock-ups that would cover a variety of flaws the robot may face during an inspection. EPRI identified that delivery systems are needed for development to increase the technology readiness level (TRL), but field deployable systems have been developed. [5]

Some of the solutions to the challenges listed above include [5]:

1. Using as few parts as practical/necessary.
2. Redundantly securing fasteners.
3. Identify whether a robotic solution completed its task intact or determine if components were left behind following the work, along with the ability to recover lost components.
4. Ensure a tether is in place to extract the system if failed.
5. The material composition of components should be assessed to ensure they do not adversely react with the DSS.

Use case application

On 3 August 2018, a misalignment event occurred while a canister (also known as a multipurpose canister [MPC]) containing SNF was being transferred to the ISFSI at the San Onofre Nuclear Generating Station (SONGS). This resulted in a special inspection which identified that contact between the MPC and ISFSI vault could occur while the MPC was being lowered into place for storage. Any deviations from the licensing basis, such as scratches or removal of protective coatings, must be evaluated to make sure those deviations do not introduce degradation to the system performance. The inspection report stated: “the failure to evaluate and disposition wear marks on a canister, if left uncorrected, could impact the adequacy of the ageing management program”. [6] The Final Safety Report for the licensed facility stated, “Because the MPC insertion (and withdrawal) occurs in the vertical configuration with ample lateral clearances, there is no risk of scratching or gouging of the MPC’s external Surface (Confinement Boundary).” [7] Therefore, this condition needed to be addressed to be able to ensure the facility was within an appropriate licensing basis.

The utility performed a visual assessment of MPCs loaded into the ISFSI using a robotic solution with a camera to measure defects. [8] This assessment used a robotic crawler developed by Robotic Technologies of Tennessee (RTT). Ref. [5] indicated the RTT crawler could traverse 90° corners and had magnetic wheels to be able to traverse carbon steel surfaces in a vertical configuration.

Figure A1.28. Image of an RTT robotic crawler on the surface of a vertical concrete canister and a close-up of a canister weld during testing at Maine Yankee [5]

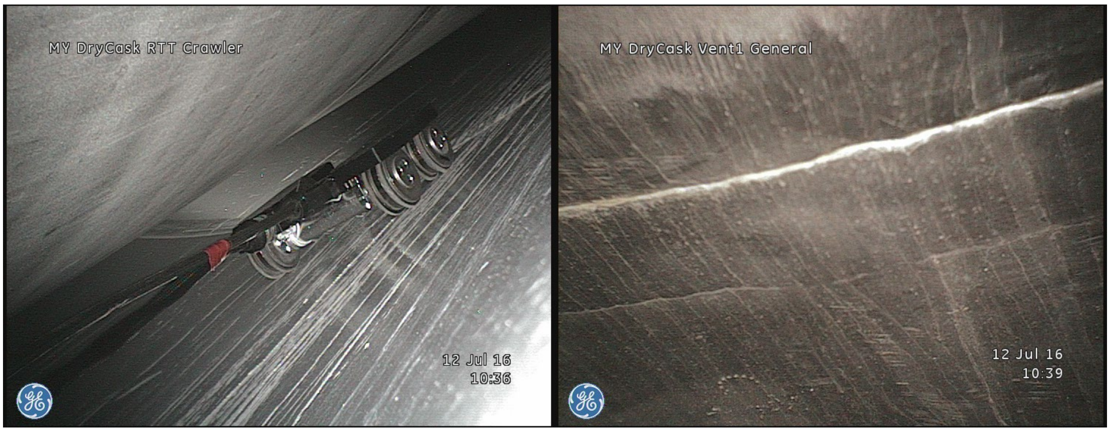
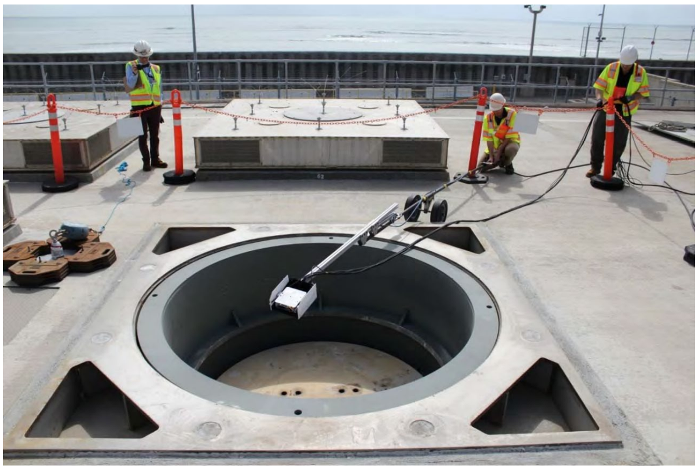


Figure A1.29. Image of the inspection robot held in a delivery tool at the loaded SONGS ISFSI vault [*9*]



The assessment involved visually examining eight canisters using a robot crawler with a GE Inspection Technologies' VideoProbe with Real3D point cloud surface scanning. The inspections covered 98% of the MPC exterior surface. The inspection was performed in a two-step process, one using a general area camera tip to locate potential surface defects, followed using a measurement tip to characterise potential defects. The robot had aluminium body and radiation-tolerant electronics. It possessed high resolution cameras and could take temperature and radiation dose measurements. [9] Their analysis concluded that a 95% probability with a 95% confidence interval that scratches on the canister during insertion and withdrawal activities would not be deeper than allowed by the applicable ASME code. An NRC inspector was on-site to observe seven of the eight visual examinations of the MPC canisters. NRC staff used the data collected during the visual examinations to independently verify the statistical analysis performed by the utility. The NRC's conclusion was the utility's analysis was conservative and reasonably bound to the maximum anticipated scratch or wear from operational activities. [10]

The utility developed a test canister to support inspections for the ageing management programme. This test canister is full-sized electrically heated MPC stored in the ISFSI and is designed to be a representative model of the MPCs housing SNF. This canister acts as a leading indicator of damage at the ISFSI. Because it does not contain SNF, it can be removed for close examination without radiation exposure to workers. If degradation is observed during an inspection, the test canister can be extracted from the ISFSI for closer inspection, and mitigation strategies can be attempted. The utility anticipates performing remote visual inspections on 2 MPCs every 5 years and on the test canister every 2.5 years. [9]

Some benefits of remote monitoring for the inspection of DSSs include the potential for dose savings to workers because MPCs could be inspected within the shielding offered by the ISFSI and potentially limiting the time a worker would spend in areas of elevated radiation. Additionally, inspections could be completed over a shorter time period, and, therefore, results could be collected and disseminated faster, because the MPC does not need to be extracted from the ISFSI and handled. By reducing the need to withdraw the MPC from the ISFSI, the chance of introducing defects to the MPC by the withdrawal and insertion process is reduced.

Along with the challenges mentioned in Ref. [5], an additional challenge could be the possibility that the robotic crawler could introduce scratches to the surfaces it is trying to inspect.

Case study references

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[2] Holtec International, “Holtec International Final Safety Analysis Report for the HI-STORM 100 Cask System”, HI-2002444, Rev. 13, Marlton, New Jersey, Holtec International, March 2016, ADAMS Accession No. ML16138A100.

[3] US Nuclear Regulatory Commission, “Managing Aging Processes in Storage (MAPS) Report”, NUREG-2214, Washington, DC, July 2019, ADAMS Accession No: ML19214A111.

[4] US Nuclear Regulatory Commission, “Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel”, NUREG-1927. Rev. 1. Washington, DC. June 2016. ADAMS Accession No. ML16179A148.

[5] Electric Power Research Institute (EPRI), “Extended Storage Collaboration Program (ESCP): Nondestructive Evaluation Subcommittee – Industry Progress Report”, Palo Alto, California, October 2017, Product ID: 3002010617.

[6] US Nuclear Regulatory Commission, “NRC Special Inspection Report 050-00206/2018-005, 050-00361/2018-005,050-00362/2018-005, 072-00041/2018-001 AND NOTICE OF VIOLATION”, Washington, DC, November 2018, ADAMS Accession No. ML18332A357.

[7] Holtec International, “Final Safety Analysis Report on The HI-STORM UMAX Canister Storage System”, HI-2115090, Rev. 3, Marlton, New Jersey, Holtec International, June 2016, ADAMS Accession No. ML16193A339.

[8] Southern California Edison, “Docket Nos. 50-206, 50-361, 50-362, and 72-41 Resumption of Fuel Transfer Operations San Onofre Nuclear Generating Station (SONGS), Units 1, 2, 3, and ISFSI”, May 2019, ADAMS Accession No. ML19141A049.

[9] Southern California Edison, “Staff Memo – Special Condition 7, CDP 9-15-0228 Appendix C: SONGS Inspection and Maintenance Program, prepared by Southern California Edison.” Memo prepared for Coastal California Commission. CDP 9-15-0228.

[10] US Nuclear Regulatory Commission, "NRC SUPPLEMENTAL INSPECTION REPORT 050-00206/2018-006, 050-00361/2018-006, 050-00362/2018-006, 072-00041/2018-002", Washington, DC, July 2019, ADAMS Accession Number: ML19190A217.

Appendix 2: Benchmarking

A.2. Summary of topical session on benchmarking at EGRRS-3 plenary meeting

Benchmarking protocols for robotic manipulation

Berk CALLI made a presentation on benchmarking for robotic manipulation. Berk Calli is an assistant professor in the Robotics Engineering Department and Computer Science Department at Worcester Polytechnic Institute (WPI). He leads the Manipulation and Environmental Robotics (MER) lab and focuses on identifying and investigating environmental research problems for robotics. He also works on fundamental research questions regarding robotic manipulation and does research on robotic grasping, control of soft robots, active vision strategies, and within-hand manipulation. Prior to WPI, he was a post-doc in the Yale University Grab Lab and completed his PhD at Delft University of Technology in the Netherlands.

Berk CALLI highlighted that interactions of robots and their environments are hard to virtually simulate and need real experiments. To support benchmarking, the Yale-CMU-Berkeley (YCB) group created a set of standard physical objects to standardise parts of the experiments. Literature was reviewed for most common objects and typical tasks performed. Objects were 3D scanned and shipped to more than 300 labs around the world, with requests still being sent today.

Experimental procedures were the next step. To increase buy-in from the robotics community, find common grounds, avoid over-fitting, improve dissemination and foster future research collaboration, multiple workshops aiming at drafting procedures were organised, with researchers from different universities working together in teams. The direct reward mechanism was publication in IEEE Robotics and Automation Special issue.

Finally, Berk CALLI presented some types of standardised protocols and presented a handful of competitions in robotic manipulations highlighted that it could be performed remotely and judged online with standard task board being provided earlier by organisations like the National Institute of Standards and Technology (NIST-US).

Identifying and addressing robotic technology gaps in nuclear cleanup

Jason WHEELER made a presentation on identifying and addressing robotic technology gaps in nuclear clean ups. Jason Wheeler is a Distinguished R&D Staff Member in the Robotics group at Sandia National Laboratories. He completed a master's degree from MIT and a PhD from Stanford University, both in Mechanical Engineering. He has contributed to or led several research programmes in robotics, biomechanics, prosthetics and control systems. He is currently leading a wearable robotics research programme focused on improving worker safety at US Department of Energy sites.

Environmental Management office of the DOE to manage and remediate the US nuclear waste legacy. Most of the simple work is completed but the challenging work remains. Considering the dangerous tasks and the ageing and diminishing workforce, the DOE-EM launched the initiative.

Benchmarking was done at a high level for the roadmap. First part was to aggregate the needs and identify applicable robotic technologies. Ranking was then based on maturity and uniqueness to nuclear clean-up operations.

Maintaining tracking process of technologies through turnover and shifts in priorities is difficult, especially as nuclear sites in the United States are discrete and do not interact between each other. Therefore, there is a constant need for cross-pollination.

Wearable robotics for worker safety have specific benchmarking protocols, and since the community of developers is still small, it is easy to keep track of advances and communicate with others

Updating the roadmap every 5 years is advised. The DOE and Sandia are interested in private and international collaboration, do not want to replicate existing efforts and are open to discussion.

Comments: Findings of the first report showed that the workers are a bottleneck for implementation of robotics. Training, ageing, reluctance, are barriers to adoption, so the safety argument is interesting. In the United Kingdom, experts in robotics are not necessarily trained in radiation while radiation trained staff is retiring or getting injuries from work on the field; these dynamics show the interest of robotics such as exoskeletons in decommissioning as a bridging technology.

Artificial intelligence assisted knowledge management

Luca PICIACCIA made a presentation on artificial intelligence assisted knowledge management.

Luca Piciaccia works as a senior consultant in the Office of the Director General of the Norwegian Radiation and Nuclear Safety Authority. He has 35 years of experience in the energy sector. He was the president of Norwegian Systems Engineering Council, and previously worked as Chief Engineer and Program Manager at Subsea Systems Engineering. He is a pioneer in the application of AI to complex industrial and knowledge management challenges. He holds several international roles both in the IAEA and the NEA with significant input on knowledge management and capacity building.

The presentation showed the opportunity to retrieve information from heterogeneous document corpus and discover patterns with the help of AI. This would prove useful for a robotics database.

Image recognition is another useful AI application nuclear decommissioning. In nuclear decommissioning setting, visual processing is difficult. However, neural networks are great for machine vision but not good at explaining their decision process: this could lead to regulation issues.

Interoperability of databases presents a bottleneck – lessons learnt are lost or not-findable. Allowing interoperability would result in “augmented knowledge” without creating new information. Addressing this would benefit the entire decommissioning field.

Machine assisted knowledge management can be superior to standard “hand-made” systems: standard systems have a fixed structure with categories and labels which are not regularly updated. It misses contradictions between former and new knowledge for instance. A dynamic machine assisted system would be more agile and could restructure the knowledge by creating a new category of invalid knowledge for instance.

Topical Session open conversation

Laurent VELNOM, the session chair, and Rustam STOLKIN, the EGRRS chair, thanked the presenters for sharing their viewpoints, which brought some very good ideas and background information to EGRRS members and participants.

Rick REID asked Jason WHEELER and Berk CALLI to clarify their definition of benchmarking in the context of the efforts they presented, and how they implement it in their field.

Jason WHEELER: In the EM-DOE roadmap context, benchmarking is equivalent to criteria which set the threshold for readiness of technology. It is difficult to create sets of benchmarking standard as the implementation in challenging environment is not compatible with tailored lab scenarios.

Berk CALLI: Their effort focuses on creating mechanisms to encourage community adoption rather than providing benchmarking protocols themselves. Efforts have to reflect the community's interests and problems to maintain involvement, it is equivalent to activation energy: if a benchmark protocol is not adopted synchronously it will die. Berk CALLI made a reference to ROSS training interns which were later disseminated in other companies, promoting the use of ROSS systems simultaneously.

Stephen SHACKLEFORD asked if there were benchmarking protocols for integrated systems, looking at the integration beyond separate functionalities. Most robotics deployed on decommissioning sites have complex functionalities overlaid with safety requirements, which makes traditional performance benchmarking inadequate.

Berk CALLI suggested that safety led to a different class of test, or could be considered as a set of constraints in which to conduct usual performance benchmarking tests. Berk CALLI highlighted that in non-nuclear robotics, the specialists pushing for safety assessments were usually found in the AI/high-autonomy branch.

Jason WHEELER remarked that implementation of robotics on the field needs two elements: a push of cutting-edge applications from academia and research, and an end-user pull by sharing needs and requirements in technical terms. In the United States there is imbalance, with mostly pushing from research and not enough pulling from end users.

Samuel COURTEILLE spoke from the operating side, mentioning that benchmarking is being used, however it is difficult to translate the results from one environment to the other. Also, at least in France, a better integration and co-operation from end-user (need), developer and research (conception) are needed in the ecosystem.

Stephen SHACKLEFORD built on the previous remark and informed the members of the UK Roadmap looking at integrating all the players of the robotics ecosystem.

Petter BERBEN noted that there are integration efforts, with practical exchanges between Germany and Belgium on how to automate radioactive waste handling.

Discussing the trade-off between performance, reliability and safety, it was highlighted that on the Sellafield site, there are currently no safety critical engineered solution driven by coded systems.

A.2. Feedback received at Digidecom 2023

Questions asked to the audience

- Have you benchmarked robotics and remote systems before?
- Is benchmarking a big part of your work and/or projects
- Would benchmarking help with the implementation of your solutions, or would it help you solve problems you encounter in decommissioning
- Would you like to have access or be in such a data base?

- Any comment on the process proposed?

Summary of the discussion

Globally

- Interest expressed from both solution providers and from end users

What would make the project successful

- Connection to other information portals with bigger user base (API)
- Conditioned by the amount of data.
- Properties beyond the technical performance will be important for users
- Instead of 0 by default, just put NA (so that it does not appear negative)

Identified limitations

- Lack of awareness and/or practicality of the database VS Google
- Speed of update to reflect advancements of the company
- Burden on supplier should not exceed too much the work done for potential clients
- Complexity of the number of categories: could be infinite

Categories to add

- Compatibility with other systems (Digidecom is promoting modularity)
- How long can it operate under X condition
- Autonomy
- Maybe should keep to TRL? (familiar metric)
- More categories to reflect mobile devices (not just arms)
- Types of radiation measurements
- Contamination viability

Unanswered questions

- How do we do with modular systems, do they reapply for each integrated application?
- Marketing plan? Business plan?
- What is the scope of technologies assessed? Is there a clear limitation?

Other comment

- Could have joint applications by suppliers for a global solution
- Many people do benchmarking internally and it quickly becomes overwhelming to compare 4-5 technologies
- Initiative could help projects and collaboration be born
- Need more emphasis on the benchmarking guidance: what would someone need to check when they do benchmarking? What is specific to nuclear benchmarking? Why is it not possible to just take technologies from other fields and apply them to nuclear?