Nuclear Energy Agency

NEA/RWM/R(2022)1

Unclassified **English text only**

12 January 2023

NUCLEAR ENERGY AGENCY

Radioactive Waste Management Committee

Status, Barriers and Cost-Benefits of Robotic and Remote Systems Applications in Nuclear Decommissioning and Radioactive Waste Management

This document is available in PDF format only.

JT03510640

Foreword

Robotics and remote systems (RRS) are essential technologies for work in the radiation environments typically encountered in the nuclear back-end, such as in radioactive waste management and decommissioning. In addition to enhancing radiation safety, there are many reasons to implement RRS, such as improving process safety and efficiency, reducing manual work or improving industrial and environmental safety.

The Expert Group on the Application of Robotic and Remote Systems in the Nuclear Back-end (EGRRS) was established under the auspices of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC) and the Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM). It supports NEA member countries in optimising the development of national radioactive waste (RW) management and decommissioning programmes through the application of robotics and remote systems.

This report is intended to support NEA member countries considering the leading and emerging RRS technologies, identify barriers to the implementation of RRS and to provide a basis for a cost-benefit methodology based on case studies of RRS applications in RW management, decommissioning and legacy management. The expert group also supports NEA member countries in enabling a wider application of RRS to encourage progress in scientific and technical knowledge and assist in the transformation towards a digital, data-driven process.

Acknowledgements

The NEA wishes to express gratitude to Miklos GARAMSZEGHY of Canada, who co-ordinated this report; to the NEA member country participants of the Expert Group on the Application of Robotic and Remote Systems in the Nuclear Back-end; and to the authors listed below for their contribution to this report:

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Martin BRANDAUER, Takune KURATA and Vladimir LEBEDEV supported this work as part of the NEA Secretariat.

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List of abbreviations and acronyms

AI	Artificial intelligence
ALARA/ALARP	As low as reasonably achievable/as low as reasonably practicable
BIM	Building information management
CANDU	Canada Deuterium Uranium
CAPEX	Capital expenditures
CBA	Cost-benefit analysis
CCTV	Closed-circuit television
CDLM	Committee on Decommissioning of Nuclear Installations and Legacy Management (NEA)
CEA	French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternative)
COG	CANDU Owners' Group
COTS	Commercial off-the-shelf
CPD	Co-operative Programme for the Exchange of Scientific and Technical Information on Nuclear Installation Decommissioning Projects
CRL	Chalk River Laboratories
DARPA	Defense Advanced Research Projects Agency (United States)
DAWP	Dual Arm Work Platform
DGR	Deep geological repository
DQO	Data quality objectives
DLTWM	Decommissioning and Long-Term Waste Management
DMCA	Digital Millennium Copyright Act
DOE	United States Department of Energy
EC	European Commission
EDF	Électricité de France
EGRRS	Expert Group on the Application of Robotic and Remote Systems in the Nuclear Back-end (NEA)

EMSM	Electrical master-slave manipulator
EPRI	Electric Power Research Institute
EU	European Union
FGMSP	First Generation Magnox Storage Pond
FIM	Fukushima Inspection Manipulator
FIU	Florida International University
FOAK	First-of-a-kind
FRM	Fukushima Repair Manipulator
FSC	Forum on Stakeholder Confidence
HIC	High Integrity Container
HLW	High-level waste
HMI	Human-machine interface
HPU	Hydraulic power unit
IAEA	International Atomic Energy Agency
ICM	International Climbing Machine
ICVD	Improved Cerenkov Viewing Device
IFE	Institute for Energy Technology (Norway)
ILW	Intermediate-level waste
INEEL	National Institute of Electricity and Clean Energy (Instituto Nacional de Electricidad y Energías Limpias, Mexico)
INEL	Idaho National Engineering Laboratory
IRS	International Rescue System
ISDC	International Structure for Decommissioning Costing
ISOCS	In Situ Object Counting System
IT	Information technology
ITER	International Thermonuclear Experimental Reactor
JAEA	Japan Atomic Energy Agency
JAMK	Jyväskylä University of Applied Sciences (Finland)
JFN	James Fisher Nuclear

JV	Joint venture
KAERI	Korea Atomic Energy Research Institute
KHG	Kerntechnische Hilfsdienst GmbH
kW	kilowatt
LAN	Local area network
LDUA	Light Duty Utility Arm
LGWIT	Lower Girth Weld Inspection Tool
LWL	Low-level waste
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
ML	Machine learning
MS	Manipulation system
MSM	Master-slave manipulator
NEA	Nuclear Energy Agency
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NEST	Nuclear Education, Skills and Technology Framework (NEA)
NIRO	Nuclear Innovation and Research Office
NNL	National Nuclear Laboratory (United Kingdom)
ONR	Office for Nuclear Regulation (United Kingdom)
OPEX	Operational expenditures
OPG	Ontario Power Generation
ORNL	Oak Ridge National Laboratory
PDP	Preliminary decommissioning plan
PNGS	Pickering Nuclear Generating Station (Canada)
PoW	Programme of Work
PPE	Personal protective equipment
PWR	Pressurised water reactor
R&AS	Robotics and automation system

R&D	Research and development
RD&D	Research, development and demonstration
RAIN	Robotics and Artificial Intelligence in Nuclear
RF	Regulators Forum
ROI	Return on investment
RoMaNS	Robotic Manipulation for Nuclear waste Sorting and Segregation
ROV	Remotely operated vehicle
RPV	Reactor pressure vessel
RRA	Robotic research area
RRS	Robotics and remote systems
RUCS	Remote Underwater Characterisation System
RW	Radioactive waste
RWM	Radioactive waste management
RWMC	Radioactive Waste Management Committee (NEA)
SCV	Spent fuel check vehicle
SG	Steam generators
SF	Spent nuclear fuel
SFP	Spent fuel pool
SMR	Small modular reactors
SRNL	Savannah River National Laboratory
SSE	Structures, systems and equipment
TEPCO	Tokyo Electric Power Company
TMI	Three Mile Island
ToR	Terms of Reference
TRL	Technology readiness level
UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
UI	User-interface

UK	United Kingdom
USSR	Union of Soviet Socialist Republics
VLLW	Very low-level waste
VR	Virtual reality
VTT	Technical Research Centre of Finland
VVER	Water-water energetic reactor
WAC	Waste acceptance criteria
WIPO	World Intellectual Property Organization
WNE	World Nuclear Exhibition
WPDD	Working Party on Decommissioning and Dismantling (NEA)

Executive summary

Robotics and remote systems (RRS) aim to reproduce or partially replace the manual tasks of humans. As such, RRS are essential for work in hazardous environments, including high radiation environments, that are encountered in radioactive waste management and decommissioning. They comprise a broad and diverse collection of technologies and a wide range of levels of automation and autonomy. These can range from simple, repetitive, pre-programmed motions to various types of smart assistance for human operators and even fully autonomously controlled robots, using artificial intelligence (AI) motion planners informed by smart sensing capabilities such as computer vision. Many of these systems are complex in themselves, and even more complex in their interactions with human operators. The technologies used in these systems also change and evolve rapidly, and will continue to do so in the foreseeable future. Recent and emerging advances in RRS offer significant potential to fundamentally change how radioactive waste management, decommissioning and legacy site remediation activities are conducted.

The Expert Group on the Application of Robotic and Remote Systems in the Nuclear Back-end (EGRRS) was established under the auspices of the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee (RWMC) and is supported by the Committee on Decommissioning of Nuclear Installations and Legacy Management (CDLM).

The purpose of the EGRRS is to support NEA member countries in optimising the development of national radioactive waste (RW) management and decommissioning programmes through the application of robotic and remote systems. The EGRRS brings together prominent international experts to advise member countries on the historical, current, emerging and future issues surrounding the implementation of RRS in nuclear applications. The EGRRS offers an important networking forum for collaboration and dissemination of knowledge and best practices between the practitioners of member countries. The EGRRS also supports NEA member countries in enabling wider applications of RRS to benefit the progress of scientific and technical knowledge and assists in the transformation towards a digital, data-driven process.

This report documents the first period of work of the EGRRS. The primary target audiences for this report are potentially interested government, institutional and private stakeholders, such as regulators, researchers, developers, implementers, service providers and funding agencies involved in nuclear back-end activities.

During this period, the EGRRS began to frame and contextualise the issues of RRS in the nuclear domain by initially investigating:

i) the status of nuclear RRS technologies in current and previous usage;

ii) a qualitative framework for appraisal of RRS usage in terms of cost-benefit analysis;

iii) the initial results from an enquiry into barriers (technological, regulatory, financial, cultural, organisational, etc.) to the deployment of RRS in the nuclear industry, as perceived by roboticists, experts in remote systems and nuclear industry end users;

iv) an in-depth discussion of a number of case study examples of previous successful RRS usage in the nuclear back-end.

There have been many applications of robotics and remote systems in nuclear back-end applications during the past several decades. It is important that the nuclear industry both publicise and disseminate these examples, and also perform independent critical assessments to identify successes, weaknesses and areas for improvement. Lessons learnt from unsuccessful applications of RRS are also important. It is expected that these will be further explored in the second mandate of the EGRRS.

The broad observations, based on the initial period of work, are that:

- More work is needed to disseminate and promote the learnings from the experiences of nuclear back-end applications of RRS in recent decades to avoid widespread duplication of effort, enable critical assessments, learn from past failures and grow a mutual understanding of best practices.
- Successful nuclear RRS applications have often been built on field-proven technologies adopted from other industries. This approach has proven to be preferable in many circumstances to beginning development from scratch.
- Other successes have been achieved simply through applying basic automation of techniques to existing systems or configuring existing processes. Where automation of repetitive motions is not possible, unstructured environments are universally tackled using painstaking direct tele-operation methods, which have changed relatively little in the past 50 years.
- However, a new generation of smart robotic technologies is emerging, with significant autonomous and AI capabilities. These technologies are expected to become strongly disruptive in future nuclear back-end activities. These technologies are evolving very rapidly in ways that are hard to predict, in an industry that plans on timescales of decades or even longer.
- In the next two decades, it is likely that systems will still be controlled by a human, but with increasing amounts of AI assistance, exploiting semi-autonomous capabilities. Evaluating and certifying the combined human-AI system will provide additional complex challenges to nuclear safety officers and regulators.
- In the nuclear back-end, use of RRS is primarily triggered by safety considerations. The effectiveness and efficiency of RRS deployment become major issues only when they have been justified by cost-saving to implement in the specific nuclear back-end activity (e.g. cost of implementation time/duration, cost of implementation of safe works with sufficient worker protection, cost of generated radioactive waste).
- Cost-benefit analysis is essential to overcome barriers to adoption. The EGRRS has developed a qualitative system of economic drivers and metrics for remote operation. This qualitative approach lessens concerns with quantitative cost-benefit assessment. These drivers take into consideration both direct and indirect effects to cover a wide range of factors which may provide economic benefits from robotic solutions. This system has been used to assess a variety of case studies, demonstrating significant benefits of RRS in these cases.

- General barriers to RRS implementation include a reluctance to use “first-of-a-kind” (FOAK) technologies and “paves the way” kinds of technology, as well as a lack of expert knowledge within end-user organisations. “Robots replacing human jobs” does not seem to be a major concern for the development and use of more advanced systems by many stakeholders, who view robots as offering significant potential to enhance the capabilities and efficiency of their expert human workforce.
- System designs should be made as flexible as practicable to enable multiple uses at a given facility as well as portability between facilities. This helps spread out development costs between projects and lessens concerns with use of FOAK technologies. Development of bespoke systems tailored to specific applications should be avoided wherever practicable.
- Service providers actually perform much of the work during facility decommissioning and can provide valuable insight into optimising task execution. It is thus critical to get service provider collaboration early in the RRS development process so that they are fully behind using the technology in the field and so that the technology development takes the needs and experience of service providers fully into account. Note that, in some cases, the service providers may be the key driving force behind RRS development and implementation.
- Younger workers are generally more comfortable with – and excited by – using RRS. The industry should take advantage of this by including younger engineers in development and application efforts.
- While use of RRS may be attractive to engineers, there may be marginal to no safety or economic benefit in using such systems for some back-end tasks. Thus, efforts should be focused on those tasks for which a clear safety or economic benefit exists.
- There is a continuing need for global collaboration in the RRS community. There are far too many examples of substantially similar systems being developed to perform substantially similar tasks in different facilities or countries. While it may encourage competition and innovation, this can waste scarce funding if left uncontrolled.
- RRS will typically operate in a challenging industrial environment, potentially including extreme temperatures, dirt and dust, elevated radiation fields, vibrations from other work, etc. Systems must be able to be reliably operated and maintained in expected environments. There have been many examples of systems failing simply due to environmental factors.
- There are several critical steps in the development of RRS. These steps should be thoughtfully performed, well documented and subject to critical review. Additionally, external stakeholders (end users, service providers, manufacturers, etc.) should be engaged early in the process for the:
    - Development of required system specifications;
    - Conceptual design, which should be subject to critical independent evaluation;
    - Fabrication of a prototype system;

  - Engineering scale prototype test, results of which are used to refine the design;
  - Cold testing (i.e. in a non-radioactive environment);
  - Field testing under prototypical conditions (i.e. in a nuclear environment).

- There is a need for a group of experts to monitor these rapidly evolving technologies and provide up-to-date expert advice to the nuclear industry so that it can keep pace and adapt in a safe and informed manner.

The EGRRS recommends additional work on RRS for the following reasons:

1) RRS encompass an enormous diversity of technologies and applications, as well as numerous different disciplines and areas of expert knowledge. Further work could address additional aspects of this large and diverse field.
2) The focus of this initial work was on documenting the current situation and the status of established technologies. This was a critical first step to frame the basic context of the work. However, a much more important and valuable step will be to develop guidance on future and emerging technologies in order to develop policies for the future role of RRS in nuclear back-end applications.
3) RRS and associated areas (such as AI, wearable robotics and sensor systems) are also unusual in that these are emerging technologies which are not at a stable state of development but advancing extremely rapidly. Today's state-of-the-art research methods are often out of date and superseded within a few months of being first published (especially the increasingly dominant role of algorithms). Therefore, it is essential that the work continue to develop and deliver advice and updates to the nuclear industry and to monitor these technologies as they evolve in ways that are difficult to predict but will have a profound impact on decommissioning and waste management methods.

1 Introduction

In the NEA Nuclear Innovation 2050 (NI-2050) initiative,[1] expert groups specified the implementation of robotics and remote systems (RRS) as a cross-cutting issue in the nuclear industry, particularly in radioactive waste management (RWM) and decommissioning. They also noted that the application of RRS should be considered in designing new, advanced reactors to enhance worker and environmental safety in the management of operational radioactive waste as well as for decommissioning. The comprehensive implementation of RRS in RWM, decommissioning and legacy management projects can improve the safety of the workers and also protect the general population and the environment.

It is acknowledged that there is a need to organise dialogue between interested parties and countries to reach a common understanding of what can be done to facilitate the way of RRS from developers to implementers and from the laboratory to industrial production, taking into account different regulatory requirements. Such dialogue could result in a foundation for the development of reports, standards and other materials, which could be further proposed to all parties for better implementation of the systems.

Nuclear decommissioning and the safe disposal of nuclear waste is a global problem of enormous societal importance. For example, decommissioning the legacy waste and nuclear facilities of the United Kingdom alone represents the largest and most complex environmental remediation project in western Europe. It is expected to take about 120 years to complete, with estimated clean-up costs of GBP 115 billion, which could rise to as much as GBP 220 billion (approximately USD 300 billion) according to current estimation protocols (NDA, 2019). These estimated costs have repeatedly and dramatically escalated over the past few decades, suggesting they may rise again. However, these cost estimates are based on current conventional ways of doing work.

In some situations with low gamma radiation where human access is possible (e.g. contaminated plutonium facilities where contaminants are predominantly alpha-emitters), decommissioning work can be carried out using human workers wearing air-fed plastic suits. However, this still results in some radiation and conventional safety risks to workers, and generates enormous quantities of secondary waste in the form of contaminated suits and other personal protective equipment (PPE). Using robotic and remote systems would reduce the risk to human workers and could dramatically reduce such secondary waste. In a variety of other situations where there is no possibility for access of human workers (e.g. high gamma radiation environments), it may not be possible to achieve remediation at all without some form of robotic or remote system.

To address these issues and provide a forum for this dialogue, the Nuclear Energy Agency (NEA) established a dedicated Expert Group on the Application of Robotics and Remote Systems in the Nuclear Back-end (EGRRS). The work of the EGRRS is motivated by the enormous potential of modern, advanced robotics to dramatically reduce these costs and greatly speed up decommissioning and remediation work, while also reducing the exposure of human workers to hazards and reducing the amount of secondary waste.

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[1] www.oecd-nea.org/jcms/pl_21829/nuclear-innovation-2050-ni2050

Despite massive and revolutionary adoption of robotics and automation by the manufacturing industry over the past 40 years, there has been remarkably little use of robotics (i.e. devices that are recognisably "robots" in the modern sense – see later discussion) in the nuclear industry, perhaps surprisingly to a layperson. The lack of penetration of modern robots into nuclear applications can be explained, for example, by the fact that:

i) Most industrial robots are designed for repetitive tasks in a well-defined, fixed environment, while decommissioning environments are often highly unstructured with significant uncertainties;

ii) the manipulations required for nuclear tasks can be extremely complex, e.g. picking up an object (such as a container or bottle) with one gripper, and performing a second action (such as removing bolts or unscrewing the lid) with a second gripper; or negotiating through tight, complex and obstacle-strewn passages to reach the intended work area;

iii) breakdown maintenance of robotic equipment can be severely complicated by high radiation environments and access limitations; and

iv) the nuclear industry is extremely conservative, with good reason, and this has sometimes made it relatively slow at introducing and accepting new technologies.

The past 15 years has seen a tremendous advance in the capabilities of robots, in particular with AI control of various kinds becoming reliably deployable at increasingly high technology readiness levels (TRLs). On the other hand, many legacy sites and structures are now ageing far beyond their original design lifetimes, e.g. 75-year-old concrete buildings containing extremely hazardous materials. These deteriorating facilities place a much greater urgency on decommissioning operations compared to previous decades. The confluence of these two forces, and a new generation of industry managers who are embracing new technology, means that the nuclear sector is now on the brink of largescale adoption of increasingly advanced robotic systems into this uniquely safety-critical and societally important environment.

1.1 Background

In 2017, the NEA Radioactive Waste Management Committee (RWMC) decided to start taking a more holistic approach[2] that would provide participating NEA member countries extensive support in the areas of radioactive waste management and decommissioning (which became the responsibility of the Committee on Decommissioning of Nuclear Installations and Legacy Management [CDLM] after April 2019). The RWMC and CDLM examined activities that would contribute to the optimisation of national programmes on radioactive waste (RW) management and decommissioning.

The broad application of advanced technologies, including robotics, was discussed in the NEA as one of the methods for such optimisation.

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[2] The RWMC stated its plan to apply a holistic, sustainable approach in organising its future activities in the RWMC Statement NEA/RWM(2019)2 (please note that this is an internal official document not available to the general public). The holistic approach considers and balances three elements: Environment, Society and Economics.

National institutions expressed the need for an international activity that would focus on the application of RRS in the nuclear back-end (NEA, 2019). In response, the NEA organised a workshop that provided a better understanding of the challenges of such a request (see www.oecd-nea.org/jcms/pl_55827). The discussions demonstrated that there was a growing interest in establishing an international initiative that would support participating NEA member countries in exploring ways to expand the use of robotic and remote systems in the management of radioactive waste, decommissioning and legacy management. The broad use of RRS in relevant projects can improve the safety of the workers involved in such projects and also better protect the general population and the environment.

However, potential end users are often hesitant to adopt new RRS techniques as they prefer equipment that has a proven track record, quality, acceptable price, increased service life, high maintainability and versatility. Some of these factors are difficult to prove for new technologies, leading to a general reluctance to adopt first-of-a-kind systems in crucial applications.

This reticence demonstrated the need for an international dialogue that would:

- establish a broader communication between RRS developers, producers, users and other interested parties to identify common terminology and understandings of problems and solutions;
- advise the decision makers on their role in support of extended application of RRS in the nuclear back-end;
- create a better awareness among potential users of the principles and processes of RRS development and a better understanding among developers and producers of the conditions of RRS operation, licensing processes and other factors to be taken into account;
- promote the development and implementation of common procedures, rules, standards, etc. (when necessary) that can significantly facilitate wider RRS implementation and that can be realised in the format of a report, guidance or other outcomes where all factors are considered, consensus between parties established, and the main points of development fixed.

The Expert Group on the Application of Robotic and Remote Systems in the Nuclear Back-end (EGRRS) was established in November 2019 to support participating NEA member countries in optimising the development of national RW management and decommissioning programmes through the application of robotic and remote systems. Based on its Mandate and Terms of Reference (ToR), the group established in its first stage (2019-2021) the objectives to:

- perform a global overview of the status of RRS application in the nuclear back-end;
- identify and analyse technical and non-technical factors which can hinder or support such applications;
- identify and document the main issues for future development.

These tasks have been performed and are documented in this report.

1.2 Group composition and scope of work

The EGRRS, as an official task-oriented third-level expert group of the NEA, is composed of 57 participants from 13 NEA member countries, which include Belgium, Finland, France, Germany, Japan, Korea, Norway, Russia (currently suspended), the Slovak Republic, Spain, Sweden, the United Kingdom and the United States. Officials from the European Commission (EC) were also actively engaged in this work, as well as observers from the International Atomic Energy Agency (IAEA).

The EGRRS was comprised of representatives of operators, research and development institutions and organisations in the field of RRS, test sites, laboratories and facilities, regulatory bodies, technical support organisations to the regulatory bodies, developers of the main and auxiliary elements for maintenance and repair of remote/robotic systems, RRS producers, suppliers and service providers, and other relevant stakeholders active in the field.

Based on the priorities established at an early stage of the expert group, the focus was placed on three major fields of activity:

- status of current technologies and uses and definition of terminology;
- barriers/impediments for RRS application;
- cost-benefit analysis of RRS implementation.

The activities carried out in these fields covered surveys, workshops and contribution papers from EGRRS participants and were the basis of this report.

2. RRS status, barriers and cost-benefit analysis

The activities in the three focus areas on robotics and remote systems (RRS) dedicated to the status of technologies, barriers to applications and cost-benefit analysis are summarised below. Further details can be found in the Annexes of this report.

2.1. Status of the use and development of robotics and remote systems in back-end applications

2.1.1. Introduction

When considering the potential use of RRS in back-end applications, it is important to understand where such systems have been used in the past, where they are currently being used, and what types of systems are under development.

Aside from providing information on potential candidate systems, such a review is useful for identifying key factors in the decision-making process, such as:

- lessons learnt, both positive and negative;
- field data on application performance and costs;
- areas of improvement for constituent technologies; and
- comparisons between competing technologies.

This information is essential for assessing the safety, cost and efficiency of potential applications. Ready accessibility of the information could also help to remove barriers to more widespread use of robotics and remote systems in the nuclear back-end.

2.1.2. Objectives

The main objective of this work was to provide a review of historical, current, and developmental uses of robotics and remote systems in nuclear back-end applications, including the pertinent information described above.

2.1.3. Origins and development of robotics and remote systems in the nuclear industry

The term “robot” was suggested in 1920 by Karel Čapek, a Czech science fiction author, to describe a humanoid walking machine and was used in many books and magazines during the two world wars to describe various types of automatic or remotely controlled machinery that mimic some aspects of human behaviour. The term was more specifically adopted by Joseph Engelberger to name an invention by his partner George Devol, who had patented a “programmed device transfer” in 1954. This led to the creation in the early 1960s of the Unimate (Unimation, today Stäubli robots), which is generally accepted as the first industrial robot.

Today, robotics is a multidisciplinary activity aiming at providing advanced automatic machines or system that can reproduce or partially replace the manual tasks of humans.

The safety constraints of radioactive materials rapidly engendered a need for some form of remote handling capability in the early days of nuclear operations. During the Second

World War, this was achieved using remote handling tongs, passing through a hole of the protective wall or through the ceiling.

The need for handling tools allowing the operator to work in a much greater working volume and avoiding working at heights was expressed around 1945 in the United States (Department of Energy/Atomic Energy Commission).

The pioneering design work was carried out at General Electric (Payne, 1948) and at Argonne National Laboratory (Goertz, 1949). An early technical report on the testing of a prototype master-slave manipulator (MSM) by R.C. Goertz appears in 1949 and it is reported that the Goertz MSM design was operational as early as 1947 (Pegman, 1997). His technology was later successfully transferred to Chalk River Laboratories (CRL), who became the leading constructor. These early MSMs (Figure 2) were still entirely mechanical and worked under the same mechanical principle as remote handling tongs, except that their arms' articulated architecture somehow mimics that of a human arm. They comprise a "master" arm and a handle manipulated by a human on the safe side of a concrete shielding wall and a kinematically similar "slave" arm equipped with a gripper on the other side of the wall in the active contaminated zone. Both arms are mechanically linked via several reversible transmissions made of steel wires, ribbons or chains linking pulleys or parallelograms. The balancing of the telemanipulator, a necessary feature to improve the quality of handling and comfort, was achieved on the first three joints, generally with counterweights.

An early archive film footage recorded at Oak Ridge shows the Payne MSM in operation. Even though the presenter describes it as a "robot", this term obviously referred more to the morphology of the master and slave arms than the working principle, which does not feature any motors, energy sources or automatic control. Another film presents its functioning principle, showing an operator as they attempt to poor liquids from glass containers.

Modern MSMs, used throughout the nuclear industry today, have changed remarkably little from Goertz's 1940s designs. The vast majority of remote handling work, at all nuclear sites in all countries, is still performed using devices that are largely similar, in design and functionality, to the 1940s machines.

As a first evolution, electric reversible servomotors controlled by analogue electronic circuits were introduced to replace the mechanical transmissions by achieving a bilateral position coupling, as early as 1954 by Goertz (EMSM, for Electrical Master Slave Manipulator). This allowed master and slave arms to be physically separated, only connected by electrical signals rather than by fixed mechanical linkages. Up to this level, the force feedback that these machines provided was only the consequence of the chosen remote mechanical transmissions. Apart from the creation by Vertut et al. in France of the MA 23, which was the first EMSM entirely actuated by highly reversible cable servomotors (Vertut et al., 1975) that inspired the technology of the first desktop master arm (Hill and Salisbury, 1977), the EMSM evolved very little until the introduction of the digital computer in the 1970s at Oak Ridge.

The computer was first used to digitalise the signals of the control loop and then for real-time computations. This made it possible, for example, to replace counterweights by computed balancing torque and Cartesian co-ordinates coupling allowing the use of different articulated structures for the master and the slave arms. These advances made it possible to create miniaturised and more ergonomic master organs and to increase the operational volume of the slave arms. A succession of incremental advances over several decades then developed these machines towards what would be more conventionally referred to nowadays as telerobotic systems.

Then, the development of back-drivable and torque-controllable joints, and the addition of force and torque sensors, enabled bilateral force feedback devices, providing the human operator with haptic telepresence. Haptic force feedback corresponds to the sense of dynamic touch and enhancesd the kinesthetic force feedback of early EMSMs by supplementing the feedback of higher frequencies involved in touch and detected in the skin rather than the muscle. Regarding nuclear applications, however, the haptic force feedback technology is not yet ready to allow remote work in a glovebox, for example (hand-to-hand tele-operation).

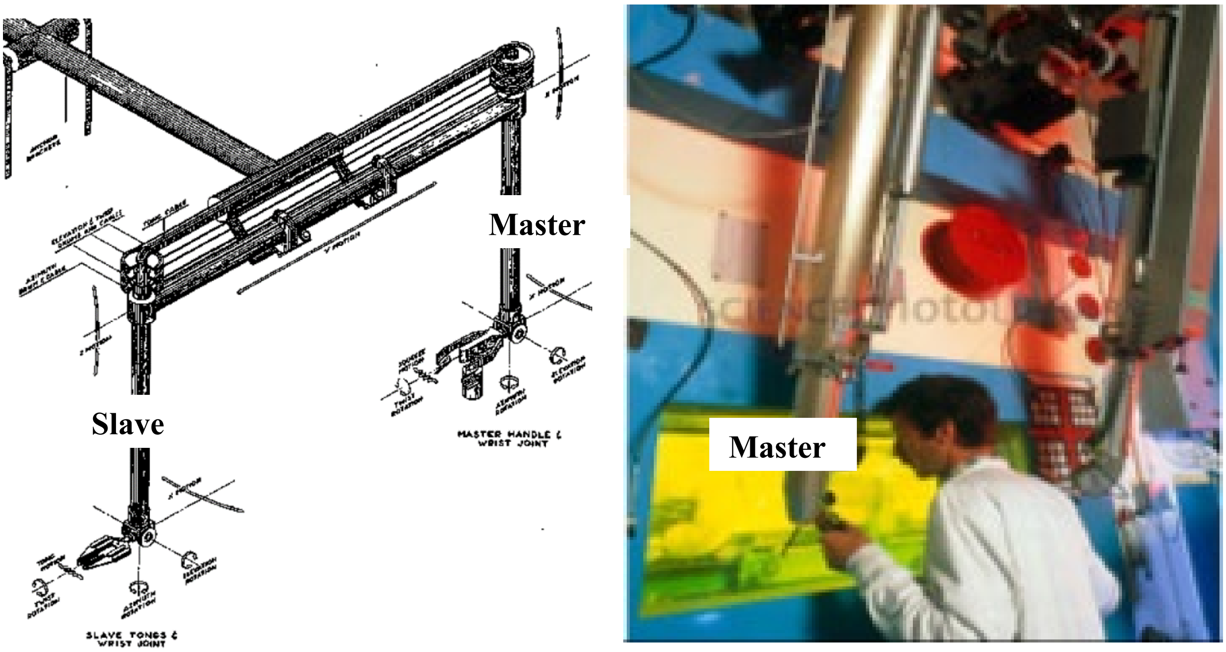
At the same time, since 2000, the considerable improvements in computers has allowed for more sophisticated aids such as artificial guides, virtual mechanisms or interactive simulation and visualisation devices (virtual reality, augmented reality). It has become possible in particular to generate contact forces in real time to improve the quality of training and the efficiency, accuracy and comfort of the operator during operations. Consequently, the perception of telerobotics by the end user has improved.

The robotics labs of nuclear agencies in Europe, the United States, Japan and other countries made pioneering contributions to all of these development stages.

Despite the above-mentioned advances, remarkably few real “robots” (in the modern sense) have been used in the nuclear industry. Recently, there have been new developments in using advanced submersible and airborne robot vehicles for monitoring and inspection in real, active zones, including underwater interventions in legacy spent fuel storage ponds (Sellafield, 2015). Various remotely operated robot vehicles (ROVs) were used (with varying levels of success and difficulty and providing different lessons learnt) to investigate nuclear accident sites including Three-Mile Island, Chernobyl, and more recently the Fukushima Daiichi Nuclear Power Plant. The use of robots at the Fukushima Daiichi Nuclear Power Plant accident site has been documented extensively (e.g. Nagatani, 2013; Okada et al., 2020; Yokokohji, 2021).

However, the above examples are relatively few and should perhaps be seen as unusual cases, especially those that feature deployments at accident sites, despite their prominence in the media and mainstream consciousness. In contrast, there are remarkably few uses of modern robotic systems for decommissioning tasks, and the vast majority of such robots deployed in the nuclear industry are still directly tele-operated in relatively rudimentary ways. The nuclear agencies of many different nations have developed and used a variety of remote systems, including innovative vehicles and pipe crawlers for deploying inspection and monitoring sensors, underwater robots, and fixed or mobile manipulators for tasks such as scabbling (Bogue, 2011). Some examples include the use of a bespoke-built manipulator for the precision cutting, cleaning and re-sealing of deteriorating pipework and a leaking concrete wall at a legacy storage pond under very high radiation dose conditions, (Sellafield, 2015a). In earlier work, efforts were made to adapt an industrial robot arm for waste drum handling and bagging operations in high dose environments (Abel et al., 1991). Hydraulic robots are widely trusted in the industry, with Brokk robots for example highly respected due to their ruggedness and reliability. However, many of these devices do not actually contain joint encoders (and some high radiation environments would damage certain kinds of joint sensors), so that inverse kinematics computation and Cartesian tool-space control with a joystick is not possible. Typically, such robots are still controlled by a human operator using separate levers to operate each joint individually, guessing the inverse kinematics from experience, while viewing the scene via CCTV cameras or through thick lead-glass windows.

Figure 1. (Left): 1949 report of mechanical master-slave manipulator (MSM) device, designed by R.C. Goertz at Argonne National Laboratory, United States. (Right): very similar devices, used worldwide today for the vast majority of remote manipulations performed in the nuclear industry.



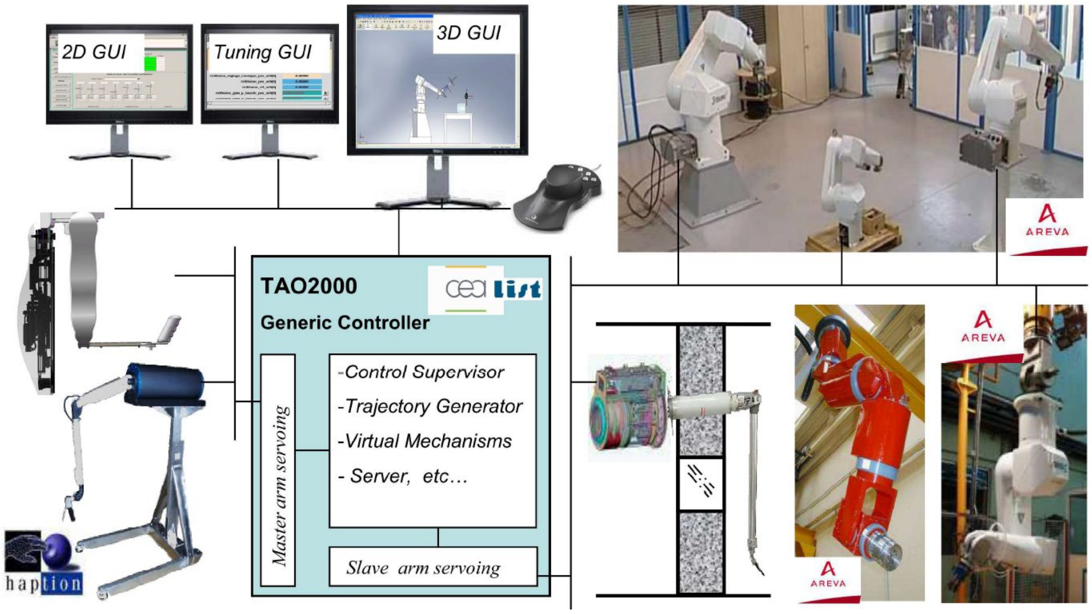
Note: In Figure 1 (right), the operator is viewing the slave manipulator in the hazardous workspace through a 1.6 metre thick lead glass window which absorbs gamma radiation. This system poses significant difficulties associated with depth perception, for example when aligning a gripper with an object, as well as ergonomic issues.

In a smaller number of cases, the industry is starting to use modern industrial robot arms with gradually more modern control methods. In recent years, Sellafield Ltd, together with UK National Nuclear Lab and KUKA Systems, has been experimenting with bespoke systems for joystick tele-operation (with CCTV camera views) of large KUKA KR500 robots. However, the baseline industry standard for controlling such robots remains limited to a pair of joysticks to control translations/rotations along/about each Cartesian axis, and situational awareness, provided through multiple CCTV cameras, is still problematic (e.g. the cognitive demands of trying to mentally fuse multiple camera views into a single 3-D mental model of a remote scene).

Pioneering work between the CEA and AREVA (Garrec, 2011) made a significant step forward in advanced control of an industrial manipulator inside a real radioactive environment, building on the CEA's work in advanced force-sensitive robotics. A six-joint hydraulic slave arm with integral force feedback was first developed as a telerobot for the dismantling workshops of the CEA (Méasson, 2011). A radiation-hardened six-axis force-torque sensor was mounted on the wrist of the industrial robotic arm, which was programmed to behave compliantly (i.e. stop and correct its motion) in response to forceful contacts with its surroundings, as shown in Fig. 2. These behaviours were then linked to a novel force-rendering haptic robot as the input master device, enabling the human operator to feel the sense of touch of the slave robot in the active environment.

Such advanced control means that a large amount of complex computation was present for the first time between the human and the robot. In this regard, the work can be regarded as a landmark case study in nuclear safety regulation for advanced computer-generated control of robots inside hazardous environments. Although the robot was tele-operated, the resulting motions of the robot in response to forceful contacts were controlled by a computer algorithm. This led to the first exchange of a series of rollers on a dissolver wheel of the reprocessing plant of AREVA-La Hague (2005). Besides, this work also demonstrated that telerobotics could be conceived as a flexible system that is likely to increase trust in advanced technologies for the end user. In parallel, a specific electric force feedback slave arm was designed to handle damaged canisters in a storage well (Goubot, 2003). This manipulator innovated with a force feedback balanced translation and the use of screw-cable actuators (CEA patents) previously introduced in the MAT6D master arm (Haption™). This telerobot is currently under industrialisation to be used in future de-storage workshops.

Figure 2. Control architecture of the CEA force-sensitive tele-operation system deployed in a radioactive environment by AREVA. Note the highly complex algorithms and software architecture that sits between the human operator and input master device (left) and the slave manipulator (right).



Source: Reproduced fom Garrec (2011).

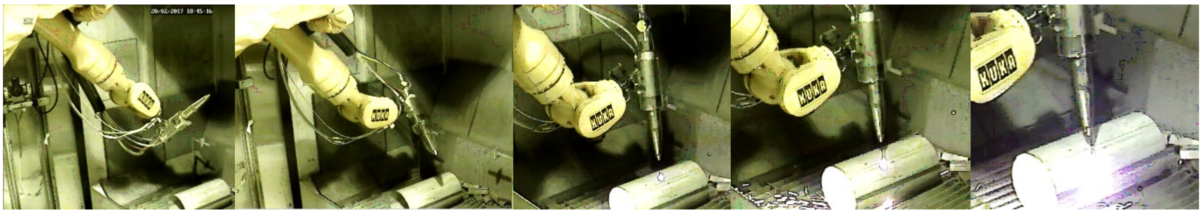
Contributing to this growth in autonomous systems in real nuclear environments, the University of Birmingham in the United Kingdom collaborated with the CEA team and other leading European robotics labs, with the UK National Nuclear Lab (NNL) as the industrial end user, in the 2014-2018 European Commission project Horizon 2020 RoMaNS (Robotic Manipulation for Nuclear waste Sorting and Segregation). This led to fully autonomous grasping (Adjigble, 2018), guided by advanced computer vision and AI motion planning, of inactive waste simulants at the NNL Workington nuclear industry site (full nuclear industry safety and national security, but a non-radioactive demonstrator). The AI grasp-planning of the University of Birmingham was also combined with the haptic input robot designed by the CEA team to yield a shared control system, in which a human and an AI collaboratively control a remote manipulator

(Adjigble, 2019), that was also demonstrated under full industry safety and security regulation.

The University of Birmingham also developed a fully autonomous, computer vision-guided, motion planning and control system for robotic laser cutting (Figure 3). This was implemented in 2016-2017 at the UK NNL's active demonstrator at the Springfields nuclear site, where a robot arm autonomously deployed a 6 kW laser to cut contaminated metal inside a radioactive hot cell (Chapman et al., 2018). It appears that this was the first time a robot arm had ever been controlled autonomously inside a radioactive environment. The addition of a powerful laser further increased the significance of this work in terms of nuclear safety regulation. Later work extended robotic cutting motion planning to the more complex case of a mobile-manipulator robot vehicle (Pardi, 2020).

This initial chapter has provided an introduction to the field of robotics and remote systems for nuclear decommissioning and waste management. These systems have evolved from being fully mechanical in the 1940s to become fully autonomous robots performing extremely hazardous tasks (laser cutting contaminated steel) inside radioactive environments. Nuclear robotics is entering a significant new era marked by growing willingness to embrace increasingly autonomous robotics and remote systems. These machines will be increasingly controlled by computers using complex robotic vision and sensing systems, with an escalating complexity in algorithms and software.

Figure 3. Autonomous motion planner guides robotic laser cutting of a curved surface, as captured by 3-D computer vision. It was the first autonomous robotic movement in a radioactive environment.



Source: Springfields nuclear site UK, 2017. Images courtesy of NNL Ltd.

2.1.4. Current status of development/activities of RRS technologies

Information in this chapter was compiled from several sources, including a survey of practitioners, researchers and nuclear safety regulators; a review of published literature; and the combined expertise of the EGRRS Status Group. While this review cannot by its nature be exhaustive, a sufficiently broad overview of the types and uses of robotics and remote systems is provided to inform evaluation of the potential benefits of RRS use for specific applications.

For ease of use, the technologies are classified into broad functionality-based groups:

- mobile robots used to deliver cameras, sensors/detectors, articulated robots or task-specific end effectors; this group includes ground units (wheels, tracks, legs, serpentines, wall-mounted suction cups), aerial, submersibles;
- articulated robots that may be mounted to stationary or mobile platforms and may be used directly to manipulate material or deliver task-specific end effectors;

- task-specific end effectors that may be mounted to stationary or mobile platforms; this may include automated or remotely controlled units for material manipulation, welding, cutting, decontamination, application of fixatives, etc.;
- control systems for remote operation of typically non-robotic systems (saws, scabblers, hydraulic rams, decontamination baths, waste conditioning or treatment systems, etc.);
- conveyors, lifting systems and mobile platforms;
- wireless data transfer and control systems;
- miscellaneous specialty systems (for example, AI systems for material sorting).

Details of various examples of applications and developments can be found in Annex B (note that these are examples provided by EGRRS participants and are not intended to be an exhaustive list of all available technologies and applications).

2.1.5. Preliminary conclusions

A wide variety of robotic and automated systems have been beneficially employed in nuclear back-end applications in recent decades and many additional systems are currently at an advanced stage of development. This information may be used by project engineers in the evaluation of field-proven technologies for the conduct of specific activities at their facilities, and by research and development groups to adapt existing solutions to specific back-end tasks, limiting the development of already existing technology. Well-publicised accounts of the successful application of robotics and remote systems in back-end applications will aid in reducing industry reticence to the use of such technologies.

The information presented in Annex B may be used as the basis to establish an interactive database of robotics and remote systems for practitioners, researchers and regulators engaged in nuclear facility decommissioning and waste management. Such a database would be invaluable in promoting the broader use of RRS in back-end applications.

An even more complex area of research is that of systems which enable a human operator to interact with an AI to control a remote robot. Such systems can be categorised as: human-supervised autonomy; shared control (Adjigble, 2019); and variable control (Chiou, 2016), where control of the robot is dynamically traded back and forth between the human and the AI. This field requires extensive considerations of psychology, neuroscience, and human factors, in addition to robotics and AI. Evaluating and certifying the safety, accuracy and reliability of the combined human-AI system will provide additional complex challenges to nuclear safety officers and regulators. On the other hand, such human-AI combined systems are likely to form the majority of advanced robot deployments in high-consequence environments in the coming two decades, as compared with fully autonomous systems. Therefore, this field will have to be embraced despite its complexities.

An important task of the NEA-EGRRS is to advise and facilitate the engagement of industry, regulators and other stakeholders with these emerging technologies. Such an international expert group is especially needed because these technologies are unusual at this point in history in that they: i) are extraordinarily complex; ii) are changing rapidly over time; and iii) should be deployed in the most high-consequence environments and applications imaginable and iv) in an unusual industrial sector that has to plan and budget for its decommissioning operations over a timeframe of many tens or even hundreds of years.

2.2. Barriers / Impediments

2.2.1. Introduction

Feedback from end users of RRS shows that reluctance to use “first-of-a-kind” technology is one of the first barriers to applying these systems. This echoes what is often heard from industry players, who talk about a “race to second place”: a reluctance to be the first to use a technology but more enthusiasm once the system has been seen to be usefully applied elsewhere in a nuclear context.

This leads to a second point – if people are unwilling to pioneer the use of a technology in the nuclear industry, how can it ever be adopted? Other great barriers include a lack of knowledge or expertise, of evidence on costs and benefits and, not least, of understanding of the social impact on end-users.

The following chapter provides a deeper characterisation of the RRS user feedback from various perspectives, including some trends that are mostly based on the survey organised within EGRRS.

2.2.2. Objectives

Within the EGRRS, work on “barriers” was established with the goal of identifying barriers and impediments that hinder the application of RRS systems in the nuclear back-end. Based on the initial challenges identified by the EGRRS (see Annex C), further challenges and ways to address them are proposed.

2.2.3. Barriers/Impediments

In addition to internal discussions to gather information from participants about the topic, a digital survey was set up on the European Union (EU) survey platform. Internal workshops, seminars and partner visits were also considered to promote the sharing of experience and feedback. The group utilised the internal webpage to support timely sharing of information and promote the collaborative review.

Identification of the impediments

To assess potential barriers and impediments to the application of RRS systems, the EGRRS identified initial challenges, which have been grouped in two categories: A) general aspects for RRS application and B) those with a particular focus on nuclear back-end activities.

Below are the perceived barriers and concerns relating to RRS implementation as elaborated by the EGRRS:

A) General aspects perceived as barriers and concerns with RRS implementation:

- current manual techniques;
- current use of robotics and remote systems;
- knowledge /awareness of currently available systems;

- reluctance to adopt first-of-a-kind technology;
- robust system demonstration data;
- broad international standards;
- formal certification processes;
- radiation hardness demonstration of RRS;
- safety authorities’ approval;
- equipment reliability;
- spare parts availability;
- maintenance requirements;
- availability of qualified operators;
- training needs;
- training requirements;
- systems use complexity;
- acceptance by workforce;
- work force concerns with job loss;
- realistic cost-benefit model;
- capital investment;
- equipment life cycle costs;
- task-specific systems;
- performance in an industrial environment vs R&D (heat, humidity, dust, etc.);
- manual effort still required;
- damage risk to critical plant equipment;
- utilities routing (e.g. power and control cables);
- systems size;
- handling of equipment/systems radioactive contamination;
- high radiation fields;
- personal safety;
- retrieving malfunctioning equipment in high radiation field;
- personal safety retrieving malfunctioning equipment;
- culture and confidence in technologies that are new and novel;
- licensing and permitting challenges.

B) Specific issues related to RRS implementation in nuclear back-end activities:

- low-level systems, e.g. hand-operated tools for underwater operations;
- automatically operated tools, e.g. programmable cutting machines;
- programmable controller with interchangeable memory, e.g. storehouse cranes;
- AI-driven tools, e.g. autonomous working robots;
- additional impediments in applications and/or test of autonomous systems in the nuclear back-end.

Digital survey to identify the relative importance of perceived barriers

A digital survey was used to identify barriers and impediments to the application of RRS systems in the nuclear back-end field. The survey questions were based on the initial challenges identified by the EGRRS.

The finalised survey was released mid-July 2020. The survey was open to any participant and anonymity was ensured. On 20 September, a Social Anthropology PhD researcher joined the group to support the survey analysis. By the end of 2020, 47 answers had been received. Details of the survey and responses are given in Annex C.

A summary of the relative importance of various barriers and concerns to implementing RRS in the nuclear back-end as perceived by the survey participants is shown in Figures 4 (summary of relative importance) and 5 (summary of total scores).

Figure 4. Summary of relative importance of perceived barriers and concerns with RRS implementation

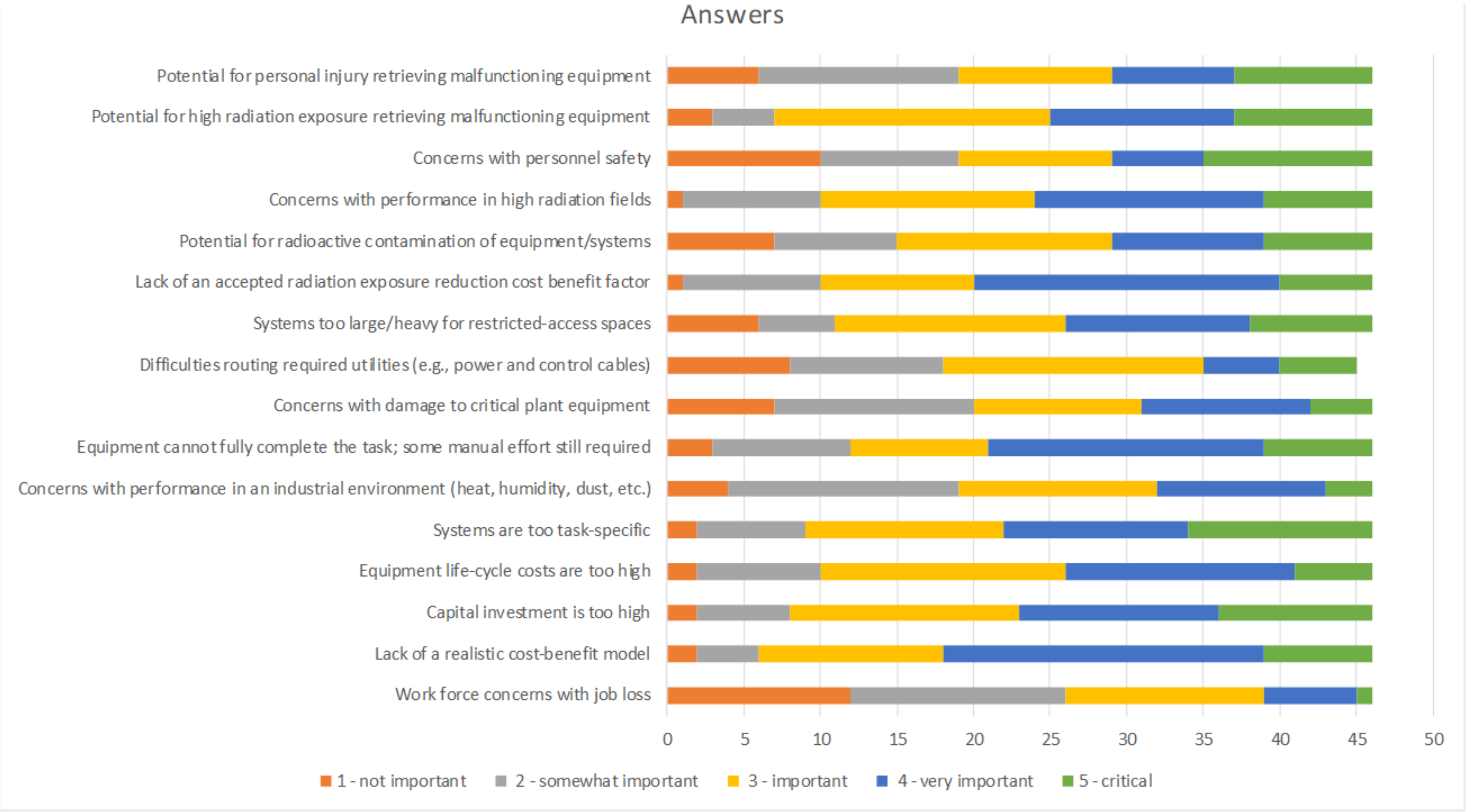


Figure 4. Summary of relative importance of perceived barriers and concerns with RRS implementation (continued)

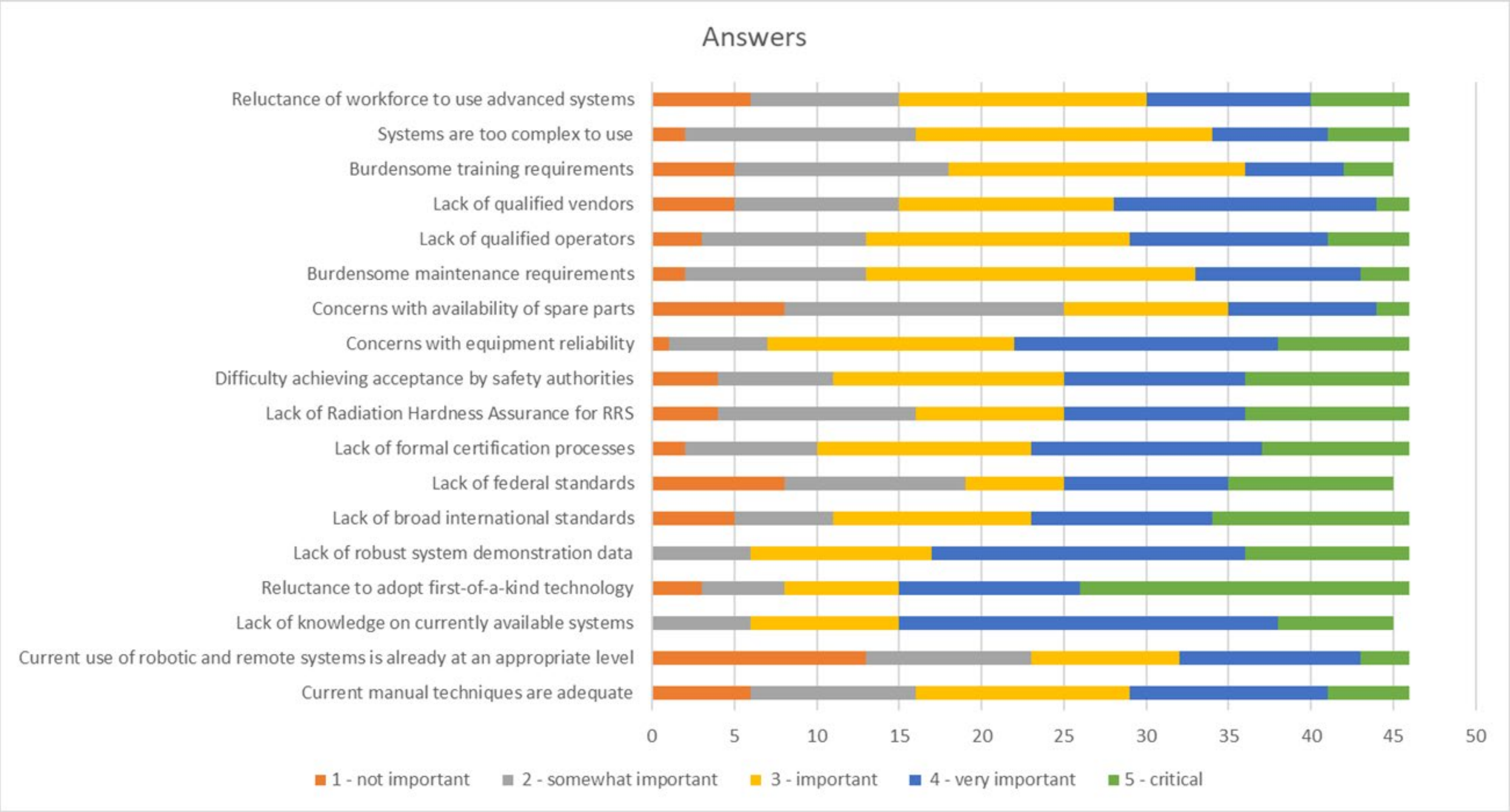


Figure 5. Summary of total scores of perceived barriers and concerns with RRS implementation

	Total	Average
Reluctance to adopt first-of-a-kind technology	198	3.88
Lack of robust system demonstration data	189	3.71
Lack of knowledge on currently available systems	186	3.65
Lack of a realistic cost-benefit model	184	3.61
Concerns with equipment reliability	180	3.53
Systems are too task-specific	179	3.51
Capital investment is too high	178	3.49
Lack of an accepted radiation exposure reduction cost benefit factor	176	3.45
Potential for high radiation exposure retrieving malfunctioning equipment	176	3.45
Lack of formal certification processes	174	3.41
Lack of broad international standards	173	3.39
Equipment cannot fully complete the task; some manual effort still required	173	3.39
Difficulty achieving acceptance by safety authorities	172	3.37
Concerns with performance in high radiation fields	172	3.37
Equipment life-cycle costs are too high	167	3.27
Lack of Radiation Hardness Assurance for RRS	166	3.25
Systems too large/heavy for restricted-access spaces	166	3.25
Lack of qualified operators	163	3.20
Lack of qualified vendors	158	3.10
Potential for radioactive contamination of equipment/systems	158	3.10
Burdensome maintenance requirements	153	3.00
Reluctance of workforce to use advanced systems	153	3.00
Lack of federal standards	152	2.98
Systems are too complex to use	152	2.98
Potential for personal injury retrieving malfunctioning equipment	152	2.98
Concerns with personnel safety	150	2.94
Current manual techniques are adequate	148	2.90
Concerns with performance in an industrial environment (heat, humidity, dust, etc.)	146	2.86
Concerns with damage to critical plant equipment	144	2.82
Burdensome training requirements	139	2.73
Difficulties routing required utilities (e.g., power and control cables)	138	2.71
Concerns with availability of spare parts	131	2.57
Current use of robotic and remote systems is already at an appropriate level	129	2.53
Work force concerns with job loss	119	2.33

It is noted that the set of results is considered small, making it difficult to establish general trends. Even so, some of the responses to the questions suggest potential for further investigation of the identified priorities.

2.2.4. Preliminary conclusions

The barrier that most respondents highlighted is the reluctance to adopt "first-of-a-kind" technologies. Adoption of new technology within the sector can be characterised as a "race to second place": if the technology has been usefully applied in a nuclear context elsewhere, adoption at another site tends to be more enthusiastically embraced. This creates a double bind, in that it is difficult to generate initial adoption and utilisation and, by doing so, provide a successful example for others to follow. The key challenge, therefore, is to build a convincing case for potential users that the technology that is in use in other industries can be utilised at a nuclear site in a safe and beneficial manner. It is worth mentioning that there are two levels to this:

- substantiation of a technology at a generic level;
- consideration of the use of the technology in a specific application.

Following from the previous point, it is therefore important to note that respondents identified several instances where a “lack of knowledge” formed a barrier to technological adoption. In order for confidence in the technology to be high enough to warrant a pioneering use of robotic systems, there must be confidence in the data supporting its use. This key barrier may exist because there is genuinely a lack of relevant, robust data supporting the case for the technology in question. The barrier could also exist because, although the data exists, it is not readily accessible, or there is a false perception within the industry that is lacking – at least as it applies in particular cases. The perception of a lack of supporting data stems from concerns about performance data, as well as a lack of knowledge surrounding the reliability of equipment and the costs of purchase and maintenance.

It is also noteworthy that the fear of job losses does not appear to be a major impediment to the adoption of robotics in the nuclear industry, according to this survey, despite being mentioned in other accounts of roboticisation (e.g. Brynjolfsson and McAfee, 2014; McClure, 2018) and in mass media. There is a lack of concern both over potential unemployment as well any changes in staff positions or retraining of operators to work with new systems. Note that this might be due to a bias of the respondents that do not include potentially affected worker groups.

It is noted that there are considerable variations in the responses. The nature of the organisation and its circumstances are important aspects to take into consideration when addressing these barriers and require more extensive analysis.

2.3. Cost-benefit analysis

While it is essential to develop robotics and remote systems from safety and technological points of view, another key aspect to consider is the cost in relation to the financial and economic benefits of their application.

The cost-benefit analysis (CBA) ad hoc group was established to provide a global view of the economic effects of robotic technologies as well as to consider practical cases with a notably positive impact. Since a global view and hands-on assessment require different methodologies, the CBA ad hoc group developed a hybrid approach to address the needs of different parties interested in the subject.

It is difficult to use quantitative metrics for a global assessment due to a significant difference in costs of similar robotic solutions. These costs can vary from country to country and even from project to project within the same country. However, the general trends and quality characteristics are the same for each application.

To provide a global review, the group developed a system of economic drivers and metrics for their qualitative assessment. These drivers take into consideration both direct and indirect effects to cover a range of factors that may provide economic benefits from robotic solutions.

To perform the relevant calculations, practical cases were identified based on experience of implementing robotic solutions with the most evident economic effects. These cases consider two scenarios of a project – with and without robotic solutions. The cases clearly demonstrate the effects of robotics used in the nuclear back-end and their advantages over non-robotic options in the examples examined. The cases also demonstrate how the economic drivers may be applied in practice.

2.3.1. Introduction

As technology continues to advance, robotic systems have been more commonly used in radioactive waste management and nuclear decommissioning. In the last decade, robots with specific capabilities have been operated in harsh radioactive waste management and decommissioning environments, remotely controlled drones equipped with sophisticated sensors have collected detailed site characteristics, and multifunctional robots have achieved safe dismantling and decontamination. Innovative techniques have enabled more cost-effective and safer waste management and nuclear decommissioning.

2.3.2. Objectives

The primary objective of the CBA work is to develop a methodology for evaluating the potential economic effects of implementing robotic technologies as well as to consider practical cases with a notably positive impact.

2.3.3. Economic drivers and methodology for analysis

Robotics and digital solutions may provide different economic advantages. However, not all of them are obvious or easily calculated. Some of the drivers are technical, some are economic and others are socio-political. All of the different factors need to be considered when making a decision over the implementation RRS technologies in a particular application.

The main drivers identified to date that have been considered in this analysis are:

- operation scheme;
- capital expenditures (CAPEX);
- operational expenditures (OPEX);
- risks;
- staffing, training requirements and competence building;
- time of execution;
- licensing and regulatory process;
- social acceptability;
- knowledge management.

Some of these drivers are similar or inter-connected and the differences and inter-relationships are described for each of them. In the context of this work, a driver is defined as having an effect on the implementation of a robotic or digital solution of a project from an economic point of view.

Other drivers which might be considered include:

- regional development (supply chain);
- research and development for future applications;
- waste minimisation;
- modularisation;
- scaling effects.

The main drivers and their assessment approach are summarised in Table 1. Details of the drivers, influences and analysis methodology are given in Annex D.

Table 1. Summary of cost-benefit drivers and assessment approaches

DRIVER	DESCRIPTION	ASSESSMENT APROACH
Operation scheme	Use of robotics vs manual performance of tasks. Will influence CAPEX and OPEX.	Indirect
CAPEX (capital expenditures)	Total capital cost of facility/system.	Direct impact. Calculation.
OPEX (operational expenditures)	Total operational costs.	Direct impact. Calculation.
Risks	Change in nature and costs associated with risks and their management.	Direct impact. Calculation.
Staffing	Total number of staff required, training needs.	Direct impact. Calculation.
Time of execution	Impact on project schedule. Related to OPEX and personnel radiation exposure.	Direct impact. Calculation.
Licensing and Regulatory process	Impact on project schedule, risks and cost.	Indirect
Social acceptability	Impact on project schedule, risks and cost.	Indirect
Knowledge management	Skills availability and retention. Related to staffing and training requirements.	Soft direct impact. Calculation.

The assessment approaches for the main drivers are described in Tables 2-8:

Table 2. Assessment approach for operational schemes

GRADE	-2	-1	0	1	2
DESCRIPTION	20% decrease in productivity. Significant negative operational impact due to impossibility of maintenance, service and repair in situ. Infrastructure is suited for humans and not suitable for certain robotics solutions	10% decrease in productivity. Negative operational impact due to impossibility of maintenance, service and repair in situ. Infrastructure is suited for humans and not suitable for certain robotics solutions	No changes operation scheme	10% increase in productivity. Positive operational impact due to better execution. Approach is more convenient for certain tasks	20% increase in productivity. Significant positive operational impact due to better execution. Approach is more convenient for certain tasks

Table 3. Assessment approach for risks

GRADE	-2	-1	0	1	2
DESCRIPTION	20% increase in expenses devoted to risk management	10% increase in expenses devoted to risk management	No changes in expenses devoted to risk management	10% decrease in expenses devoted to risk management	20% decrease in expenses devoted to risk management

Table 4. Assessment approach for staff

GRADE	-2	-1	0	1	2
DESCRIPTION	20% increase in staff expenses	10% increase in staff expenses	No changes in staff expenses	10% decrease in staff expenses	20% decrease in staff expenses

Table 5. Assessment approach for time of execution

GRADE	-2	-1	0	1	2
DESCRIPTION	20% increase in execution time	10% increase in execution time	No changes in execution time	10% decrease in execution time	20% decrease in execution time

Table 6. Assessment approach for licensing and regulatory process

GRADE	-2	-1	0	1	2
DESCRIPTION	20% increase in costs or time of licensing of robotics and digital solutions	10% increase in costs or time of licensing of robotics and digital solutions	No difficulties in licensing of robotics and digital solutions	10% decrease in costs or time of licensing of robotics and digital solutions	20% decrease in costs or time of licensing of robotics and digital solutions

Table 7. Assessment approach for social acceptability

GRADE	-2	-1	0	1	2
DESCRIPTION	Significant opposition by local community to using robotics and digital solutions in decommissioning (publications in media, legal action and rallies against the topic)	Low opposition of local community to using robotics and digital solutions in decommissioning (publications in media, law initiatives and rallies against the topic)	No influence on local community	Consent by local community on using robotics and digital solutions in decommissioning	Consent by local community on using robotics and digital solutions in decommissioning

Table 8. Assessment approach for knowledge management

GRADE	0	1	2	3	4
DESCRIPTION	No influence on knowledge management	Knowledge accumulation – database	Semi AI solutions and/or predictive analytics and/or database and education skills	No more than two of the following: - AI solutions developing best approaches and improving execution skills; - predictive analytics and decision-making systems; - massive database with wide range of information and knowledge	All of the following: - AI solutions developing best approaches and improving execution skills; - predictive analytics and decision-making systems; - massive database with wide range of information and knowledge

2.3.4. Cost-benefit effects for different applications

When deciding on the role of human intervention in RRS applications, the following points could be considered, among others:

1) Can this environment be safely entered, and the tasks be safely managed, by human workers with PPE?
    - If so, what is the amount of hazard including dose and other forms of potential harm?
    - What amount of secondary waste would be generated by large numbers of human entries, and what additional risk and cost is associated with the processing and storage of such waste?
2) Alternatively, is this task or environment impossible to handle with human entries?
    - If so, what is the cost and risk of the liability of this task remaining unresolved?
    - How do these issues weigh up against the costs, risks and other issues of RRS deployments?
    - What issues arise in terms of robotic systems themselves as a contaminated waste stream, comprising a complex mixture of elements and compounds e.g. circuit boards or batteries, at end-of-life and disposal?

To support the understanding and provide a basis for further development, participants of the group identified two case studies for robotics and remote systems applications described in the following.

Example: cost-benefit-considerations for waste sorting with automated/remote systems

The former fuel assembly manufacturing plant in Dessel, Belgium, stopped operation in 2012 and the decision was then taken to dismantle and denuclearize the plant with the intention of an unrestricted site release. To support this goal, a 100% screening of the groud was adopted with large quantities (~ 38 000 tonnes) of excavated soil. This has been characterised and sorted by a belt conveyor system, shown in Figure 6 below, while comparison to manual characterization is offered. Please find additional details in Annex D (Cost Benefit Analysis Methodology). Taking from the case, the economic effects can be reflected in CAPEX and OPEX. As mentioned above, the quantitative metrics can vary from country to country and the costs depend on the projects.

Figure 6. FREMES Conveyor belt automatically sorting the radioactive waste by HPGE Gamma Spectroscopy in Dessel, Belgium.

Note: Top part shows the process flow, bottom part shows a close up of the free-release waste pile at the end of the belt.
Source: Images courtesy of NUKEM.

The case study results show that, given the right boundary conditions, in the long run, robotics and remote systems provide the opportunity to achieve both lower capital and lower operational costs. The analysed case covers the performance of a belt conveyor free release measurement system for radiological characterisation of concrete and construction waste (denoted FREMES) compared to 20 ISOCS (In Situ Object Counting System) examining the same volume of soil. The initial CAPEX of FREMES is 29% lower than 20 ISOCS, based on a 6-year life cycle. Given that the FREMES life cycle is designed for 16 years while ISOCS is set to 6 years, the estimated improvement could be even higher than the 29%. The OPEX of FREMES is half that of 20 ISOCS. The case reflects the general trends for such an application.

Example: Cost-benefit-considerations for dismantling steam generators of nuclear power plants

The practical approach in this case includes assessments of the economic efficiency of using robotics and remote systems in the dismantling of nuclear power plant steam generators (SG). This represents a specific challenge, since:

- Like reactor vessels, SG are part of the highly contaminated massive equipment of a nuclear power plant.
- Dose rates require increased radiological protection measures (reducing occupational time, zoning, shielding, personal protective equipment [PPE], rehearsals and mock-up) with the associated need to implement additional resources for organising safe, effective and efficient work (technical, intellectual, know-how, funding) but also to organise safe, effective and efficient management of secondary waste produced (e.g. used PPE).
- Even after performing system decontamination of SG, dose rates remain high.
- Dismantling of SG will produce higher-level radioactive waste, from contaminated inner components and surfaces, that will have to be managed.
- Besides the direct costs, the time necessary for dismantling SG impacts the overall time for dismantling, which implies indirect costs (e.g. for maintaining structures, systems and equipment [SSE], organisational and technical infrastructure for safety and physical protection [security] of the nuclear power plant).

A safe, effective and efficient approach requires specific solutions for the dismantling of large, contaminated components with respectively reduced dose uptake and optimised RW management.

The typical principal approaches for dismantling steam generators (or other similarly large, contaminated components such as heat exchangers, reactor vessels, etc.) are in situ versus ex situ fragmentation (off-site, rip-and-ship approach), both meant to minimise dose uptake with extensive use of remote means.

In the case of ex situ fragmentation, the steam generator or component needs to be moved out of its original location to a site which has been configured specifically for fragmentation: this allows a higher degree of use of remote and automated systems because boundary conditions can be configured as required. An example that demonstrates the effectiveness of this approach is the decommissioning of the Greifswald Nuclear Power Plant in Germany (VVER type reactor): SG are removed in one piece for fragmentation in a special caisson, which is part of a new building erected adjacent to the nuclear power plant and comprises storage and dismantling facilities. This approach contributed to reduced dose uptake for workers and fragmentation performance by increased use of remote tools and systems. These advantages, however, come at the cost of rather high investments (CAPEX) to create the necessary infrastructure, which may be advantageous if there is a sufficient number of large equipment such as SG to be dismantled. Other examples from Germany include:

- SG from the Stade Nuclear Power Plant, which were decontaminated and shipped with very light shielding to Studsvik in Sweden for further treatment, minimising the amount of radioactive waste remaining; and

- SG from the Obrigheim Nuclear Power Plant and the Rheinsberg Nuclear Power Plant, which were shipped to the Greifswald Nuclear Power Plant and will be dismantled there for further treatment, minimising the amount of radioactive waste remaining. (One great way to avoid radiation exposure in the Greifswald Nuclear Power Plant is to increase decay time. They have 30 SG from Greifswald, 2 from Obrigheim and 9 from Rheinsberg. Dismantling is occurring at a slow pace to increase decay time.)

In situ fragmentation is more challenging in terms of remote systems and automatisation. When the nuclear power plants were designed, there was no specific consideration of measures to optimise the dismantling and fragmentation of the installed systems and components, and certainly not for possible use of remote or robotic systems for in situ fragmentation. The conditions to implement this approach are therefore rarely favourable.

There is an interesting alternative approach which has demonstrated its effectiveness in practice and was developed for the Bohunice Nuclear Power Plant in the Slovak Republic (VVER type reactor): the steam generator is moved in one piece from its original place to the adjacent turbine hall, which had been emptied and modified to include space for the fragmentation and RW management works. In this area, a mobile platform with a multi-freedom robotic arm has been installed on which special fragmentation tools can be mounted. The system is remote-controlled with the support of automated (programmed) sequences (e.g. the positioning of the cutting tool to start cutting is controlled by the operator, the cutting itself is performed by a programmed routine involving real-time data collection and processing during the cutting operation). The cuttings are automatically collected and handed over to a remotely controlled device configured to collect and place the cuttings in intermediate storage containers for transfer to the next RW management step. This system, initially conceived primarily as a R&D demonstrator, was successful enough to justify the decision to enhance its use for fragmenting a series of six steam generators in a sequence, and was implemented successfully. Some key performance features:

- There is no need to transport the steam generator over long distances as the workplace is prepared within the existing premises of the nuclear power plant.
- The technology can be operated remotely in a highly automated regime (digital process control support for the operator), in which the movement of each tool and fragment is kept under control.
- The net fragmentation time is reduced by 15-25% by utilising a circular milling cutter for the casing (vessel) and a high-speed circular saw to cut pipes.
- Beside fragmentation time, the radiation exposure is further reduced by decreasing the number of staff necessary for the fragmentation process.
- The reduction of involved staff contributes to a reduction in secondary waste (i.e. PPE) generated.
- The capital expenditures (CAPEX) for the configuration, including providing the fragmentation workplace and system in the former turbine hall, have been lowered by about 30-35% in comparison to other options considered.

2.3.5. Preliminary conclusions

This work defined economic drivers, their effects and assessment approaches for potential CBA of RRS. With the analysed case studies, it was demonstrated that, from a cost-benefit point of view, there are oportunities for the successful application of RRS in the nuclear back-end. The economic favorability, however, depends very much on the boundary conditions of the application, the complexity as well as the drivers identified in this work.

3. Discussion

3.1. Introduction

The nuclear industry makes extensive use of remote handling systems to implement technological processes in radioactive environments and comply with radiological protection and safety requirements, according to the ALARA/ALARP (i.e. as low as reasonably achievable/as low as reasonably practicable) principle. These systems are almost exclusively mechanical – remote clamps, booms, master-slave remote manipulators – that have not changed significantly for several decades. They are used particularly in research laboratories, in nuclear fuel production units and even in some nuclear power plants.

This technology has slowly evolved with some applications in nuclear laboratories and attempts in decommissioning sites. Some of these systems have been integrated into vehicles to create post-accident intervention vehicles. At the beginning of the 1980s, these types of systems were digitalised and progressively enhanced with computing capabilities allowing assistive functions and supervision, ultimately leading them to merge with robotics in the telerobotics concept.

Since then, the applications of robotics, telerobotics, and remotely operated systems (RRS) in the nuclear back-end have been modest compared to the high potential of these technologies. Nevertheless, there have been convincing uses of some systems (telerobots with force feedback, mobile robots with manipulator or even robotic arms) during the last 20 years for dismantling and maintenance tasks of high added value. This experience makes it possible to highlight the complex factors that can favour or slow down the deployment of increasingly advanced robotic technologies in the nuclear industry. In particular, it has been shown that these technologies can benefit both the quality of work in the domain of delicate tele-operated tasks (assistive guides, supervision) and productivity when there is repetition of tasks.

The evolution of applications and developments in the nuclear sector is demand-driven, as in other industrial sectors. As in all competitive industrial sectors, the main demand is for the production of efficient and robust systems at affordable prices and competitive with alternative solutions, with the additional pertinent requirement of nuclear and radiological safety (criticality control and radiological protection). In the nuclear industry, RRS systems that are remote and dexterous, and therefore under real-time human control, have always been decisive success factors in establishing and/or maintaining safety, while automatic or autonomous systems are justified by the need for productivity (competitiveness) as well as by the robustness and safety allowed by modern technologies. In any case, all these applications must follow and integrate continuously the developments induced by economic and/or regulatory requirements. Note that currently, for new facilities, the owner very seldom incorporates into the design of the new facility a “robot friendly” section. This often leads to complex retrofitting issues when such a technology is added later.

In an active power plant with a highly structured environment, the handling of, for example, fresh and spent fuel rods, whose size and shape are exactly known, is carried out without human presence and under predictable conditions. These applications therefore lend themselves to traditional methods of automation and robotics, where (as in manufacturing environments) operations can be carried out using simple actuated systems performing pre-programmed, repetitive movements.

In contrast, spent fuel reprocessing is a complex activity with variable tasks to be performed in hot-cells. It involves RRS for remote handling with human expertise and is, therefore, systematically guided by radiological protection principles. The maintenance of these installations also requires complex interventions on high-value components involving RRS.

The other downstream activities, namely characterisation, decommissioning, clean-up and management of nuclear and radioactive waste (including disposal), are driven by the same imperatives. However, unlike the two previous cases (power plants and spent fuel reprocessing), the demand here is not driven by productivity imposed by commercial profitability, but rather by safety requirements. Accordingly, the focus is on resolving challenges related to existing effluents or situations safely and efficiently without a revenue-generating product for an end consumer. This has the effect that decisions about design and configuration are primarily not driven by considerations of return of investment (meaning generating or increasing revenues based on investments) but primarily by reducing costs for a necessary “lost investment” (meaning without direct return except possibly cost-saving). Accordingly, many nuclear back-end activities are following less the logic of industrialisation of processes with high productivity, but more the logic of project management with a focus on cost management and necessary safety requirements. The focus on cost management as well as licensing may hinder investments into advancing novel and emerging technologies.

Uncertainties, which can accumulate and become financial risks, must be weighed against the potential short-term savings achievable through higher productivity.

Decommissioning (especially old and aged legacy facilities) often presents a highly unstructured and/or unreliable environment, with associated large uncertainties. The management of legacy sites, legacy inventories, accident response or post-accident situations are exceptional challenges for the nuclear sector, requiring decommissioning and radioactive waste management to achieve a safe end state. Many nations have a significant number of legacy sites, posing significant challenges.

For example, waste streams can include complex mixed materials (e.g. contaminated rubber gloves and PPE, broken concrete, metal and construction materials) as well as non-radioactive hazardous materials (e.g. asbestos, lead, PCBs) that cannot be handled by robots or automated machinery on the basis of simple pre-programmed motions and actions. These are highly unstructured environments, in which the currently viable way to use robotics is by a human directly controlling (teleoperating) the robot. This is why the first answer has traditionally involved large amounts of slow and painstaking tele-operation of remote robots by human workers, using rudimentary control systems and CCTV cameras for situational awareness. It is questionable whether such approaches can achieve clean-up tasks at legacy sites in socially acceptable timeframes given the quantity of material involved. Advanced RRS such as tele-operation using assistive guides, supervision and virtual reality can certainly improve the quality of work and working conditions of the operators but should be reserved to only delicate and high-value tasks because the presence of a human limits productivity.

For these applications, advanced AI-assisted robotics could represent an effective tool to significantly reduce delays. However, to further “automate” such interventions, significant technological progress will be required because the objective is essentially to build machines that are sufficiently “intelligent” that they can partially take over the control currently performed by humans. This requires a step change from the most rudimentary tele-operated machines (e.g. joystick controlled) to autonomous robotic systems that must go beyond the current state-of-the-art in AI and intelligent software and sensory systems. Note that such a step change essentially jumps over the intermediary graded stages of conventional, repetitive, pre-programmed robotic actions. The level of automation is characterised by a large spectrum, ranging from assistance to fully autonomous solutions. The intermediary graded stages were highly successful in the manufacturing industry over the past half century (see, for instance, the SAE Classification J3016 in the automobile industry [SAE, 2019]), but it was only possible because of the highly structured and constrained manufacturing environment (e.g. known products arriving in known positions on a production line). Also in the field of oil exploration, such a graded approach gained some momentum in the application of RRS.

Furthermore, where the presence of humans is required and tolerable in situ, wearable robotic solutions (including small passive systems as well as exoskeletons) have the potential to further support work, especially in labour-intensive areas.

It should be noted that there are some non-technological barriers to implementing RRS more widely. One such barrier is related to intellectual property rights. For example, the US law Digital Millennium Copyright Act (DMCA) is a United States copyright law that implements two 1996 treaties of the World Intellectual Property Organization (WIPO). Passed on 12 October 1998, the DMCA amended Title 17 of the United States Code to extend the reach of copyright, while limiting the liability of the providers of online services for copyright infringement by their users.

Among the provisions contained in the text there is the possibility of explicitly prohibiting the circumvention of technologies used to protect documents subject to copyright. Thus, the law prohibits the misappropriation of copy protection, but also distributing or making available processes that allow this misappropriation.

Also, in the EU, Directive 2001/29 / EC of the European Parliament and the Council of the European Union "On the Harmonization of Certain Aspects of Copyright and Related Rights in the Information Society" was adopted on 22 May 2001 to implement the WIPO Copyright Treaty and harmonise various aspects of copyright law throughout Europe, including copyright limitations and exceptions.

Based on these laws, producers can seriously restrict access to information about their products, including the information needed for service needs (handling, repairing, re-programming, etc.).

Producers propose their own services which often appear expensive compared to smaller independent service providers. Only official service centres are usually provided with needed documentation that restricts other service providers.

The official service usually supposes the replacement of the whole block instead of more precise (and sometimes cheap) intervention. As a result, "electronic" waste has been growing in many countries recently. In the case of the nuclear back-end it means the growth of radioactive waste. Also, the producers can extend the service time without risk of being replaced by more accurate service organisations. Each time, the producers refer to the legislation protecting their behaviour and it is not easy to find a compromise.

Taking into account the complexity of RRS, such policy can lead to situations where the implementer finds it is easier and cheaper to buy new equipment than to get service from all suppliers.

Another issue is the so-called artificial ageing that some producers include in the design of their products. This pushes users to buy the same products during periods that are beneficial for the producers, and it leads to extra spending, which have no reason except to benefit the producers.

Furthermore, there is a lack of a standard that would allow the development of integrators and create the necessary confidence among end users. Indeed, since the industrialists specialised in mechanical or electronic remote handling are small, they cannot handle the investments needed to evolve towards advanced robotics. There is a risk that their valuable expertise will disappear. A standard that would allow the constitution of on-demand systems would favour their specialisation and increase their chances of survival. On the other hand, the end user would have a guarantee of durability, not of the system but of its function.

All these factors could have a negative influence on RRS application in the nuclear back-end and may lead to the need for some exclusions in the application of relevant legislation being considered (e.g. "right to repair" legislation being considered in some countries).

In this context of intersecting economic and technological constraints, it is possible to outline in more detail the experience of, and potential for, using RRS in the nuclear back-end in the following fields:

- robotics in spent fuel management;
- robotics for radioactive waste management;
- robotics for nuclear facilities decommissioning;
- robotics for the management of legacy facilities and post-accident situations;
- robotics in accident response.

3.2. Robotics in spent fuel processing

Spent nuclear fuel (SF) is usually managed through two main strategies: reprocessing and disposal.

This spent nuclear fuel can be reprocessed once, with the fissile portion used to make new fuel. Once this fuel itself is spent, disposal is the final solution. Alternatively, the SF can be reprocessed each time it is removed from the reactor.

In both strategies, the primary storage in the spent fuel pool is the first stage of management. After that, the SF is usually transferred from the reactor zone to the dry storage facility (centralised or at the nuclear power plant site) where it is stored, waiting for further management (disposal or reprocessing). Various storage strategies could be implemented (short-term, long-term or even extended storage). Depending on the case, monitoring, handling and possibly repackaging operations may require the application of RRS. During storage, container handling, container monitoring data collection and management are the challenges. Transporting SF containers from one stage to another requires numerous remote-controlled operations. Thus, in SF management, RRS application can support the following operations:

- Retrieval of SF from reactors to the spent fuel pool (there are technologies for these operations such as loading machines); the specific issue could be the retrieval of damaged assemblies and fuel debris; also, new types of fuel can require the application of newly developed RRS for their management.

- The interim storage in spent fuel pools requires the monitoring of the fuel's status, handling the SF containers/assemblies within the pools and extraction and packaging for transfer to the next stages; the management of damaged assemblies andfuel debris within pools is a specific issue.
- The transportation of SF between facilities requires the application of various remotely operated techniques.
- During storage, containers with SF require periodic inspection (for integrity, temperature and other parameters); transfer of containers within the storage facility might be needed; addressing the degradation of both SF and containers during the extended storage, the repackaging will require RRS to be used.
- New RRS samples and methods will be needed for the handling of SF containers within the disposal facilities (deep geological repository, or DGR). In some concepts of DGR, the un-/re-packing can be required before placing SF assemblies in the disposal chambers, and that implies RRS application. The disposal of new types of fuel can also be considered in the context of RRS application. During the DGR operation, a lot of safety (radiation and industrial) functions can be performed by RRS (fire safety, excavation works, sealing of filled chambers, internal transportation of non-radioactive materials, monitoring of the integrity of containers, barriers and constructions, emergency response and rescue operations and many others).
- SF reprocessing is currently largely automated; however, an improvement in techniques and methods could be considered useful; in the case of new reprocessing facilities, new RRS could be developed to be integrated into the new facility.
- In the case of SF from research and other types of non-energetic applications, the specific RRS configuration could be needed for the management of SF; specific issues could appear with the implementation of new advanced reactors (small modular reactors [SMRs], floating nuclear power plants, Generation IV reactors and others); as some SMRs are expected to be installed in remote areas, the specific requirements of RRS would need to be formulated.

The specificity of SF management requires some advanced features of RRS, for example:

- Remote work and process flow are mandatory for safety requirements due to the high radioactivity.
- The high radioactivity resistance of sensors is an issue.
- High precision (no miss) is required in operations; SF management operation means the handling of heavy containers with high legibility of positioning.
- Maintenance and repair with some types of techniques can require other specific types of RRS.

- Handling and manipulation of fuel under water (including measurements and sampling).
- With progressing automation, increasing security requirements.
- Adaptability to handling different types of fuel, especially in transport, storage and disposal facilities.

3.3. Robotics for radioactive waste management

According to the international consensus reflected in international standards (IAEA, EC and others), the RW must be managed in a safe manner up to and including disposal. Due to the wide variety of RW types, diverse management strategies are applied. The main factors defining the selection of methods of management and final disposal solution include:

- RW volumes;
- RW class (HLW, ILW, LLW, VLLW) based on activity and half-life;
- RW physical state (solid, liquid or gas);
- type of packaging (e.g. materials, containers);
- current location and transport requirements;
- chemical composition;
- origin of the RW (when included as a part of a waste classification system);
- the main isotopes in the RW (radiotoxicity, mobility, chemical activity, etc.);
- evolution over time due to decay.

The management of RW is not limited to RW from nuclear energy production. RW is produced in almost all front-end activities as well as other sectors such as medicine and mining, and this RW requires safe management.

According to the NEA-RWMC holistic vision, the management of RW can be conditionally broken down in the following stages:

- RW generation, collection, characterisation, sorting and primary packaging (if applied);
- RW treatment and conditioning (some RW classes and types could be untreated or unconditioned);
- RW storage (interim for both conditioned and non-conditioned, long-term for all types of RW; storage for decay for very short-lived RW);
- RW disposal.

Radioactive waste management typically comprises:

- Direct taking over or retrieval from a buffer or interim storage of raw RW – normally in preliminary waste packages; however, RW is often stored in old storage facilities for a long time, not conditioned or even packaged. And the retrieval of such waste can require the characterisation of the storage and then the characterisation of each portion of extracted waste. Sometimes, an old facility once designated for "disposal" can require waste retrieval, and this is a specific challenge.

- Characterisation of waste is an important operation, which makes it possible to minimise the waste volume through the accurate separation of radioactive and non-radioactive waste. In the case of large volumes of RW, RRS can be extremely useful. However, equipment with high sensitivity and specificity of measurement is needed to increase the level of separation.
- Preliminary sorting of wastes is based on the characterisation, and a high level of reliability of measurements is a crucial factor; the application of the RRS allows a quick sorting of large volumes of RW.
- Processing and conditioning (if applied) of waste, depending on the waste class and technology applied, can be equipped with robotics or remote systems; this can be especially useful in the treatment of HLW and big volumes of lower-level waste (ILW, LLW). The conditioning of RW is followed by the collecting and handling of large volumes of information (information about the RW and treatment, package passport, transfer of relevant data to the next RW management stages, etc.) which can be performed with the usage of RRS.
- Retrieval and repackaging of historical RW including additional processing and conditioning, size reduction of empty packaging (to be re-packaged in new containers), etc.
- Disposal of RW is the final point of RW management. The disposal strategy is identified based on the RW class, the available disposal routes, the safety case and waste acceptance criteria (WAC) of the receiving facility as well as other factors. RRS application in disposal facilities can be an important optimising factor. In addition to RW handling, RRS can also be used in disposal facility operations providing fire safety, excavations, tunnels maintenance, monitoring, maintaining and repairing of constructions and engineering systems, etc. Information/data/knowledge management in disposal facilities can also be facilitated through RRS application.
- A rather specific RW management activity is the collection and consequent management of RW from small producers (e.g. scientific activities; medical applications, disused sealed radioactive sources [DSRS]) where RRS can play a more visible role.
- The facility security provision can also widely apply RRS.

The performance criteria for the deployment of RRS in waste management are typically:

- protection of the personnel, population and environment, minimisation of risks (dose);
- minimisation of waste management costs: optimised waste formation, RW volumes of different categories (e.g. better and more reliable sorting), optimised time of RW management (e.g. improved process throughput);
- improvement of RW forms and waste packages (e.g. better quality control and consistency, improved inspection capability).

There are numerous benefits in using RRS with advanced automation for homogeneous RW streams. Good examples include liquid radioactive waste treatment plants (e.g. process control for filtering, evaporation, solidification), treatment of LLW and ILW solid waste (e.g. incineration, compaction) and automated sorting of low-level, decommissioning bulk wastes (e.g. dismantling debris with low contents of residual contents of contamination). The automated control is quite straightforward and most of the situations can be managed by simple decision-based programming such as that used in standard industrial process control equipment (e.g. single, or few, parameter if-then-algorithms, interlocks and logic gates). The current optimisation potential is probably mainly in complementing existing solutions with integration of up-to-date sensor equipment, data processing and analysis tools for the furthering fostering of effectiveness (reducing failures or overburdening) and efficiency (productivity, maintenance optimisation) as also continuously adopted in non-nuclear industry.

The challenge for nuclear operators and decision makers, however, is integrating and implementing rapidly growing and changing technologies. The risk is that installed equipment (hardware and software) may become obsolete quickly, resulting in difficulties in maintaining the equipment as well as in updating facilities or repurposing them in a safe and economical manner.

For heterogeneous RW streams, the challenge is considerably greater: different compositions must be recognised, and decisions made to select the appropriate path and process to achieve an optimal result. Although obvious in principle, this requires a combined interaction of different technologies and disciplines: for example, for characterisation, sorting, and processing, automated control is much more difficult and typically requires advanced artificial intelligence algorithms at various stages of pattern recognition, deep analysis, self-correction or self-programming. In the R&D field, highly versatile, flexible and self-organising systems have been demonstrated and are continuously developed. However, their application in the real industrial environment is still limited due to the insufficient maturity of the technology and the limits of implementing incremental solutions in an economically efficient manner. The uncertainties and risks of partial or larger failures are an argument for decision makers and implementers to wait for a real-world reference case to be established.

It should be noted that large-scale decommissioning projects (e.g. the Ignalina Nuclear Power Plant in Lithuania, Bohunice Nuclear Power Plant in the Slovak Republic, Chernobyl Nuclear Power Plant in Ukraine, Sellafield site in the United Kingdom, Savannah River National Laboratory [SRNL] and Hanford sites in the United States) have fostered the development of complex facilities for radioactive waste management with extensive use of remote technologies which are (or can be considered) operational. Each situation is unique, varying in scale, funding and timing, which affects the degree of RRS applied. In addition, it may be noted that many if these reference cases were typically publicly financed. Private industry is typically more risk-averse with regard to the use of advanced complex technologies given the uncertainties of investment return. Reference cases are therefore an important enabler for RRS. For existing facilities, it may be interesting to note that they are typically equipped with man-operated remote digital control systems, which may be quite easily further modernised by introducing increasing (graded) automated control components with increasing AI elements to support human operators to operate these complex facilities more productively. Again, a paced and graded approach can support and reduce the technological gap between developers and implementers.

3.4. Robotics for nuclear facilities decommissioning

Dismantling of nuclear facilities presents a specific range of challenges including:

- characterisation, dismantling and fragmentation of highly contaminated systems and components, e.g. reactor internals, reactor vessels, primary circuits, steam generators (high activity concentrated in a small, often massive volume);
- characterisation and dismantling of contaminated buildings and structures (heterogeneously distributed moderate activity in specific parts of building and structures);
- characterisation and dismantling of buildings and structures with low or no contamination (occasionally low activity dispersed locally in larger volumes);
- characterisation and management of bulk materials (e.g. soils) with low or no contamination (typically low activity dispersed in larger volumes).

In the performance of decommissioning work in a radioactive environment, the following types of RRS tools can be observed:

- specialised tools adapted for fragmentation of highly contaminated equipment and systems, either typically remotely operated by a human operator (e.g. cutting and retrieval of reactor internals) or sometimes with partially or enhanced automated systems with software assisted control (e.g. cutting reactor vessels or steam generators);
- multi-versatile robust mobile equipment or carrier platforms with interchangeable tools configured for radioactive environments (often called dismantling robots), which are typically remotely operated by a human operator;
- specialised systems for automated monitoring and segregation of bulk materials (soil, rubble, etc.).

For an environment with no or very low occasional radioactivity, robust and versatile mobile equipment with interchangeable tools such as those used in civil construction work may be observed. Conventional safety hazards, such as asbestos, PCBs and lead, must also be considered. In the absence of remote control (which would be quite exceptional) for radiological protection and the application of the ALARA principle, common provisions are implemented to reduce the risk for the operator of respiratory or percutaneous exposure, such as breath delivery units (BDU)/ventilator control, an overpressure air-conditioned cabin, or PPE.

These observations may confirm that automation in dismantling works is still quite limited and may be justified better in a high-dose environment. In a low-dose environment, the justification would be probably similar to the one of conventional dismantling works where the use of RRSs is also not very common. The most promising tools in this area are in semi-autonomous characterisation and 3D-scanning of buildings. Another example is final decontamination of the remaining buildings and facilities, which is currently mainly a manual activity with workers in suitable PPE. The pattern changes for decommissioning waste management where semi-automated or automated systems for sorting and clearance of decommissioning wastes are frequently observed in practice because of their typical justification: minimising waste disposal costs.

It is interesting to note that a complete RRS system integrating characterisation and decommissioning would be an exception in practice, so it is possible to improve RRS systems for decommissioning, if the decommissioning organisation wishes to use them.

3.5. Robotics for management of legacy facilities and post-accident situations

The challenges of managing legacy facilities and post-accident situations are typically associated with non-normative conditions and inventories under challenging conditions, including substantial uncertainties.

However, they are real situations and activities may be planned, licensed and implemented addressing specifically the non-normative conditions and uncertainties. Technical solutions typically imply addressing specifically the safety for known and uncertain nuclear and radiological conditions during implementation. In these technical solutions, given this context and the mostly harsh working environment, RRS might become a primary option. More specifically, situations characterised by non-normative conditions of nuclear or radioactive inventory, chemical hazards and including possibly unstable conditions due to damaged structures, infrastructure, systems and equipment with a certain degree of uncertainty and often unique or unprecedented elements (no reference case) are drivers for RRS.

In practice, use of remotely operated equipment is a common approach to organising retrieval and radioactive waste management (e.g. remotely operated dismantling equipment, automated classification and sorting of rubble). Systems and tools similar to those used for the dismantling of (highly) contaminated structures can be used.

The control of the equipment is typically extensively made by operators with a rather limited level of automation and limited productivity. This may be explained by the individual specificity of each case, which does not make it possible to revert easily to existing systems. At the same time, these applications need to show visible progress instead of investing time and resources for research and development, which may be considered as adding to lost investment.

3.6. Robotics in accident response

Emergency response in case of significant accidents requires an ability to take action in an unplanned situation, with a high degree of uncertainty with typically high relevance for nuclear, radiation and industrial safety.

In principle, such a situation would be predetermined for the use of RSS to minimise human intervention for collecting data to reduce uncertainties and take immediate action for hazard defence (if possible in-depth) to protect the general public, the workers and the environment.

The main peculiarity of an emergency situation in case of significant accidents is, however, that the unplanned as well as effective and efficient deployment of RSS requires ad hoc resources, such as:

- Availability of effective RRS for specific required or desired tasks where typically the identification of tasks in terms of objective, scope and priority (survey, manipulation) are not predetermined and are evolving during the emergency at the nuclear site.
- Availability of operators who are trained on these RRS and have sufficient knowledge of the nuclear sites where the emergency occurred; these

operators should preferably be selected from among those who regularly work as remote operators in dismantling shops. Thus, the development of RRS for dismantling applications represents the best guarantee of having expert operators available for post-accident situations. Indeed, operators of specialised post-accident intervention groups can hardly benefit from a sufficiently intense and varied training. In addition, their equipment, which is less frequently renewed, cannot claim to have the best performance. Thus, the development of RRS for dismantling applications represents an irreplaceable guarantee for having expert operators in post-accident situations.

- Availability of appropriate infrastructure and supporting systems, including operators for these RRS at the nuclear site where the emergency occurs.
- Availability of existing RRS to be adapted easily and quickly to newly discovered conditions of operation.

In practice, while availability is limited and adequate preparation is required, any available RRS is a tool and option for:

- active risk management by the operator of the plant (including cost-benefit-management as far as reasonably possible ad hoc in an emergency);
- optimised use of available RRS in combination with other systems (e.g. plant workers, external supporting resources, including robotic specialists) by adapting ad hoc to the situation and needs to the extent reasonably possible.

Experience shows that specialised emergency response organisations (e.g. Kerntechnische Hilfsdienst GmbH [KHG] in Germany; Naraha Robotics Centre for Remote Control Technology Development [NARREC] of the Japan Atomic Energy Agency in Japan) with long-term over-annual budgets have a specific role and the possibility to develop specialised RRS for emergency response with mobile infrastructure (e.g. mobile remote operating base, mobile power supply) and maintain a trained team which may be deployed in an emergency situation.

These specialised emergency response organisations do not supersede the responsibility of a site operator to take action but are a valuable option to support the site operator with specific specialised RRS on a demand and purpose basis. The value of the option can be increased by:

- implementation of specialised infrastructure for the use of own or external RRS to be better prepared for emergency cases (e.g. access corridors, high-speed communication equipment [transponders for data transfers], power supply systems, control devices, control room, trained staff);
- specific training including simulation of emergency cases with RRS operators of the plant operator to be better prepared for an emergency case – with support by robotics experts from the specialised emergency response organisation;
- co-operation – organisation of work: task splitting/distribution among different available systems and resources, including for on-site-emergency response systems, specialised RRS provided by the emergency organisation, use of available technology and staff from the operator;

Advanced informatic systems including AI to support the operator and emergency response teams to support overview and decision-making during an emergency case and to deploy RRS may be a further option for:

- resource optimisation: use of available resources including staff, tools and RRS. RRS is not an objective but an option (in complement to other resources);
- safety optimisation as part of risk optimisation: implement dangerous work with staff as much as necessary as low as possible; optimisation should cover all types of regulating (nuclear safety, fire safety, industrial safety, etc.);
- cost-benefit optimisation: minimising time and resource utilisation to achieve increasingly safer statuses;
- security issues (when applied);
- the improved use of RRS in the field of emergency response in case of heavy accidents requires a lot of R&D, which is not easy for an operator of one or several sites to plan but may be fostered by co-ordinated transboundary efforts (e.g. experience exchanges, training, R&D).

3.7. Conclusions

General conclusive statements:

- The general evolutionary sequence of RRS can be summarised as:
    - Mechanised equipment → remotely operated → IT assisted → automated → autonomous (increasing automation grade)
- Tele-operation by humans is needed because the unstructured environments frequently encountered in waste management and decommissioning do not lend themselves to repetitive automation. This results in a profound challenge because further “automation” means machines that can do the job of human intelligence in controlling the remote robot in unknown environments. This requires AI and “autonomous” robotics which remains an open research challenge for this application.
- The AI challenges in this case include: diverse and changing “unstructured environments”; the ability to “generalise” and have a “semantic level understanding of scenes and objects”; the ability to correctly handle uncertainty and have “situational awareness”.
- The development of AI is further challenged by a lack of availability of reference cases, digital and simulation models, suitable development environment (e.g. robot base, trained operators, reliable human-machine interface [HMI], digital twin/shadow) and specific regulatory requirements. In addition, the duration of planning, design, licensing and implementation is difficult to incorporate into most project schedules.
- Safety and economic benefits are generally the main drivers.
- RRS are common in some parts of the nuclear industry (including in the nuclear back-end). However, there is large potential for additional deployment.

- In the nuclear back-end, use of RRS is primarily triggered by safety. Effectiveness and efficiency become a major issue only when it is justified by cost-saving to implement the specific nuclear back-end activity (e.g. cost of implementation time/duration, cost of implementation of safe works with sufficient workers protection, cost of generated radioactive waste).
- The primary focus is typically on remote work, which may have a different degree of automation: the mechanisation of work → remote operated execution of repetitive work in well-defined boundary conditions→ remote operated execution of flexible (multi-versatile) and varying work sequences under changing boundary conditions.
- Another focus which typically becomes important (if it is justified by cost-saving) is the level of automation: operator (human) direct control → remote operator control with remote feedback (bidirectional human-machine interface) → computer-assisted operator control (use of programmed sequences on a decision of operator) → semi-autonomous computer-assisted operator control (use of programmed sequences using AI elements for motion and work optimisation on a decision of operator) → autonomous device (most of the decisions are shifted to AI-based IT systems, leaving the operator to make only the main decisions, using a graded approach).
- The increasing use of RRS with increasingly automated or autonomous elements opens several substantial options to foster safe, effective and efficient solutions in the nuclear back-end, which represent an opportunity for further development.
- However, the systems and the associated technologies (e.g. sensoring, technical configuration, information technology [IT] including AI systems) are increasingly complex, going beyond the capabilities and the limits of single solutions for individual cases, which should be compensated by modularisation. Co-ordinated exchanges and R&D-efforts beyond the individual organisation and national boundaries are necessary, which makes specific involvement of multi-national organisations and transboundary programmes necessary.
- Besides the technical aspects of RRS, the use of RRS with increasing autonomy is also an increasingly challenging issue for regulatory aspects, which will require further efforts and co-ordinated developments between the relevant stakeholders.
- In case of new reactors, such as SMRs, it could be useful to design and/or construct specific RRS directly with the development of the SMRs.

4. Summary and conclusions

This report documents the first period of work of the EGRRS. During this period, the EGRRS began to frame and contextualise the issues of RRS in the nuclear domain, by initially investigating:

i) The status of nuclear RRS technologies in current and previous usage;

ii) the initial results from an enquiry into barriers (technological, regulatory, financial, cultural, organisational, etc.) to the deployment of RRS in the nuclear industry, as perceived by roboticists, experts in remote systems, and nuclear industry end users;

iii) a qualitative framework for appraisal of RRS usage in terms of cost-benefit analysis;

iv) a set of in-depth case studies of examples of previous successful RRS usage in the nuclear back-end.

Initial findings and broad conclusions are listed in the following. It is furthermore supported by the summary of the findings collected during the "EGRRS Dedicated Contribution at the Online Event Focusing on Innovation within Nuclear Decommissioning at DigiDecom 2021" on the 25 March 2021 [https://www.oecd-nea.org/EGRRS21].

In terms of current status and previous usage of RRS:

- Annex B documents a wide variety of robotic and automated systems which have been beneficially employed in nuclear back-end applications, and additional systems at an advanced stage of development. This information may be used by project engineers in the evaluation of field-proven technologies. (Note that these are examples provided by participants and are not intended to be an exhaustive list of all available technologies and applications.)

- Annex B may be used as a basis to establish an interactive online database of robotics and remote systems for practitioners, researchers and regulators engaged in nuclear facility decommissioning and waste management. Such a database would be invaluable in promoting the broader use of RRS in back-end applications.

- A more complex emerging area of research is that of systems which enable a human operator to interact with an AI to control a remote robot. Evaluating and certifying the combined human-AI system will provide additional complex challenges to nuclear safety officers and regulators. On the other hand, such human-AI combined systems are likely to form the majority of advanced robot deployments in high-consequence environments in the coming two decades, as compared with fully autonomous systems. Therefore, this field will have to be embraced despite its complexities.

- These technologies are unusual in that they are complex and evolving and changing extremely rapidly over time. Additionally, they should be deployed in an unusual industrial sector that has to plan and budget today for its future decommissioning operations over an extraordinarily long time frame of many tens or even hundreds of years.

In terms of barriers and impediments:

- One of the most significant barriers reported by stakeholders is a reluctance to use “first-of-a-kind” (FOAK) technology. This echoes what is often heard from industry sources who talk about a “race to second place”; people are reluctant to be the first to use a technology, but more enthusiastic once it has been usefully applied elsewhere in a nuclear context.
- This leads to a second point – if people are unwilling to pioneer the use of a technology in the nuclear industry, how can there ever be justification for it being adopted in the first place?
- Another major barrier, based on a broad characterisation of various categories, is a “lack of knowledge or expertise” in the back-end field.
- The next aspects to be considered are the lack of evidence for cost-benefit analysis and, not least, the social impact at end-users’ facilities.
- Contrary to popular perception, loss of jobs to robots does not seem to be a major concern among most respondents. However, this is identified as a concern among some respondents.
- A notable difference in opinion was observed between the various types of organisations. It has been observed that developers of the technology believe that the vendors (potentially themselves) are qualified, whereas the industry has concerns in this regard.
- It is important to note that there is a wide diversity and disparity in responses from a wide variety of different stakeholders. Hence it is important for RRS developers to obtain a deeper understanding of the drivers and constraints of particular end users.

In terms of cost-benefit analysis:

- It is difficult to use quantitative metrics for a global assessment due to a significant difference in costs of similar robotic solutions from country to country and even from project to project. However, general trends and qualitative characteristics are the same for each application.
- To provide a global review, the EGRRS has developed a system of economic drivers and metrics for their qualitative assessment. These drivers take into consideration both direct and indirect effects to cover a wide range of factors which may provide economic benefits from robotic solutions.
- A set of case studies was identified based on the experience of successfully implementing robotic solutions with evident economic effects. These cases consider two scenarios of a project – with and without robotic solutions. The cases clearly demonstrate the effectiveness of using robotics in the nuclear back-end and their advantages over non-robotic options in these situations. The cases also demonstrate how the provided economic drivers may be applied in practice. (The initial work focused on successful implementations. Additional case studies, including examples where there was no demonstrable benefit from RRS, will be examined in the next phase of the work.)

This report has examined and documented many successful applications of robotics and remote systems (RRS) in back-end applications during the past several decades, and such systems continue to be used today. It is important that the industry both publicise these successes and perform independent critical assessments to identify weaknesses and areas for improvement. Broad observations from these case studies include:

- Many successful nuclear applications have built on field-proven technologies adopted from other industries. This approach has proven to be preferable to beginning development from scratch.
- Other successes have been achieved simply through automation of existing systems and processes, or configuring existing technologies for remote operation. This approach lessens concerns with use of FOAK technologies and paves the way for incremental development and use of more advanced systems.
- System designs should be made as flexible as practicable to enable multiple uses at a given facility as well as portability between facilities (such flexibility is a key strength of the concept of "robot" as opposed to "automation" machinery). This helps spread out development costs between projects and lessens concerns with use of FOAK technologies. Development of bespoke systems tailored to specific applications should be avoided wherever practicable. Service providers perform much of the work during facility decommissioning. It is thus critical to get service provider collaboration early in the development process so that they are fully behind using the technology in the field.
- Younger workers are generally more comfortable and in fact excited by using RRS. The industry should take advantage of this by including younger engineers in development and application efforts.
- While use of RRS may be attractive to engineers, there is only a marginal known cost-benefit advantage in using such systems for many back-end tasks. Efforts should be focused on those tasks for which a clear benefit exists.
- There is a continuing need to find ways to improve global collaboration and dissemination in the RRS community. There are far too many examples of substantially similar systems being developed to perform substantially similar tasks, by different teams at different sites. This duplication of effort wastes scarce funding.
- RRS will typically operate in a challenging industrial environment, potentially including extreme temperatures, dirt and dust, elevated radiation fields, vibrations from other ongoing work, etc. Systems must be able to be reliably operated and maintained in such environments. There have been many examples of systems failing simply due to environmental factors.

- There are several critical steps in the development of RRS. These steps should be thoughtfully performed, well documented and subject to critical review. Additionally, external stakeholders (end users, service providers, manufacturers, etc.) should be engaged early in the process. These critical steps include:
    1. Development of required system specifications.
    2. Conceptual design that should be subject to critical independent evaluation.
    3. Fabrication of prototype system.
    4. Engineering scale prototype test, results of which are used to refine the design.
    5. Cold testing (i.e. in a non-radioactive environment).
    6. Field testing under prototypical conditions (i.e. in a nuclear environment).

5. Future work

In the following, a general perspective is given resulting from the work done by EGRRS from 2019 to 2021, and the future development of EGRRS is illustrated.

5.1. Key challenges of future and emerging technologies

One of the challenging and, at the same time, promising factors considered by the EGRRS is the rapidly evolving approaches, functionalities and capabilities of AI, ML and other smart algorithms, linked to smart sensors and perception systems. These are increasingly being applied in the control of robotic systems, and also have a role in the collection and analysis of data, e.g. "characterisation" in legacy nuclear facilities, and in data-informed decision making. These technologies offer enormous potential, and are likely to be profoundly disruptive in the near future. However, they also introduce a number of difficult open challenges, especially when deployed in high-consequence environments. These include, for example, issues of verification and validation of increasingly complex systems, comprising many hundreds of thousands of lines of computer code, spanning numerous software libraries created by large numbers of individuals. The smarter and more autonomous a robotic system becomes, the less predictable its actions will be. Additionally, machine learning introduces potential for robotic systems which change their own decision-making processes in real time during operational deployments. These issues feed directly into considerations of safety and risk assessments, and thereby also issues of regulation, liability and policy.

An additional emerging area, of great scientific complexity, is that of human-machine interaction. This includes the design and development of human-robot interfaces (both cognitive and physical with e.g. haptic systems). It also includes the questions of how to objectively measure and characterise the performance, safety and other factors, of systems in which both human workers and AI's interact to co-operatively control remote robotic systems. The addition of the human- in-the-loop adds great complexity to an AI system that is alreadyso complex. These technologies are evolving extraordinarily fast. The latest algorithms are often superseded and obsolete within a year, especially in areas such as computational vision systems. The functional capabilities of smart robots have been making large step changes roughly once per every five years over the past two decades – and robotic hardware and sensory hardware have also been transforming roughly every five years.

High-speed of solving decommissioning tasks rapidly will require training both new specialists in creating and control RRS in dangerous conditions and retraining of current employees. The creation of common international educational programmess will require constant updating in case of if they are to following the pace of development in RRS and based on successful application experience during decommissioning.

There is thus a significant danger, that regulation and policy decisions will be already outdated and obsolete by the time they are implemented. There is also significant danger that poorly designed regulation can significantly obstruct the development and introduction of innovative new technologies.

Some of the key challenges include (not limiting):

- The deployment of RRS requires some degree of harmonisation of the legal framework between the countries.
- Analyse impact of robotics on nuclear energy sustainability across the globe and compliance with the UN Sustainable Development Goals.
- Promote standards to assist with safety cases and deployment types.
- Promote a standardised approach to RRS hardware and software making for plug and play technology within nuclear robotics. Investigate having a robust, deployable toolset of approved robotic technology that has been verified and validated for a given scenario. This offers a repeatable and reliable baseline for nuclear deployments and the foundation for further enhancements such as AI or machine learning (ML) stretching towards human-supervised autonomy and beyond.
- Support dialogue and exchanges between the main involved stakeholders: operators and implementers, regulators (in nuclear and other robotic areas), designers and producers of RRS, scientists, service organisations, public organisations and others.
- Provide recommendations and proposals for international R&D co-operation and co-ordination to facilitate development and implementation of robotic solutions.
- It is important to determine how the ageing of the equipment is managed and how to maintain and/or update/replace the operating system in place. The main reason is because the control electronics of the RRS usually have a useful life of only a few years before they become obsolete, while the nuclear facilities in which they will be used have a useful life of several decades.

These unusual and unprecedented challenges provide a strong need and motivation for establishing a long-term ongoing international co-ordination effort on this topic. The EGRRS has brought together the leading experts from numerous nations and provides an ideal platform for delivering this critical monitoring and advising function moving forward.

5.2. Future perspectives of the EGRRS work

The RWMC created the EGRRS in 2019 to elaborate, in a stepwise manner, the guidance for NEA member countries on the establishment of national frameworks allowing the broad industrial-scale application of robotic and remote systems (RRS) at all stages and in all activities of the nuclear back-end. Also, the EGRRS scope of work includes RW management and decommissioning activities not related to the nuclear power plant – research, medical, transport and other nuclear applications.

For the first step, within two years, the RWMC defined the EGRRS goals as the overview of the current status of RRS in the nuclear industry, collection of information, and primary analysis of the key factors influencing the application of RRS. The EGRRS successfully performed the objectives mandated by the RWMC, and developed this report based on the collected and analysed information.

In 2022, the EGRRS starts its second two-year period of work with new objectives:

- Develop a systematic approach for comprehensive benchmarking of best practices in RRS applications (database implementation);
- Provide an iterative process of solution-finding towards the identified barriers in the regulatory framework (with regulators, operators, developers, technical support organisations [TSO], etc.);
- Develop a cost-benefit methodology/structure for RRS application in the back-end field, providing a decision-making tool on the “human” vs “robotics” task;
- Analyse the future implications of emerging AI and advanced robotics technologies, approaches and functionalities, while monitoring new developments and synergies as they emerge, and advising participating NEA member countries on future implications and emerging opportunities.

As an important basis for the implementation of RRS in the nuclear field, education and training will also be addressed by the EGRRS. It is proposed to formulate the requirements of general education programmes for studying new specialists in the field of RRS development and operation.

The group will continue to collect and analyse the information through the exchanges between participating NEA member countries, and identify the good practices of RRS applications. This can lead potentially to the creation of a database, and the EGRRS can provide a set of recommendations concerning the functions and main features of such a database.

As a practical example in an emerging field, the use of RRS in the construction and operation of deep geological repositories (DGRs) for spent nuclear fuel and high-level wastes can be further studied in conjunction with the RWMC. Alternate construction technologies, such as robotic tunnel boring machines, show promise as a safer, more efficient method for DGR construction. In addition, operation of a DGR will also require robotics and remote systems due to the inherently high radiation environment. Therefore, it is expected that the EGRRS will also extend its activities and surveys to these fields and identify impediments or barriers to the application of RRS in DGR construction as well as RW management and decommissioning.

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Annex A: EGRRS Matrix

The kick-off meeting of the EGRRS identified some of the influencing factors and associated challenges in the areas defined as i) technical, safety and environment, ii) economical, iii) societal, iv) legal and regulatory and v) organisational and structural. Given some of the identified topics and challenges fall in different areas, cross-cutting aspect were collected at the bottom of Table 9. Topics that are relevant in two or more areas are color coded.

Table 9. Key influencing robotics and remote systems factors

	Topics				
	Technical, safety and environmental	**Economical**	**Societal**	**Legal and regulator framework**	**Organisational and structural framework**
Systematic description of the status and challenges	• First of the kind application challenge • Transference from human to AI • Multi-purpose use/ cost-efficiency • Grading of autonomy • Application bringing together end user and developer • Standardization • Foot-print of robotic application / secondary waste • Maintenance and intervention concepts • Adapting existing technologies • Standard approaches (e.g. grinding) • Tracking of waste streams	• First of the kind application challenge • Multi-purpose use/ cost-efficiency • Societal and economical benefit from radiation protection and other hazards • Business case (commercialization) • Unknown AI challenge • Identification of investment needs • Justification of investments • Use of the RRS in routine activity -> maturity • Opportunities for new economical activities (services)	• Transference from human to AI • Educational factor • Societal and economical benefit from radiation protection and other hazards • Lack of willingness of technology in the back-end (traditions, ageing work force) • Encouragement of students/young professionals in back-end (WM) activities • Perception of replacement of work place (high-value jobs being created at the same time) • Improve public perception of nuclear/ AI (the unknown) • Distinguish social and human challenges (the why question) / collective and individual view point • Liability associated with automation, AI, etc.	• Grading of autonomy to ease the application • Gap between the regulatory framework and the used/existing technology • Way to implement innovation • Standards • Not to make it more strict as necessary • Benchmarking of technology/ reproduction of results/ technology validation -> mechanism of how to address this! • Relevant state policy / provision • Certification • Specific Radiation Hardness Assurance process	• Educational factor • Lack of recommendation where to use robots and what point we need to start considering robots • Organizational changes implied by the applications of RRS • How to minimizing gap between end user and developer • Inform benefits and costs • Keep R&D realistic and optimized • Adapted existing practices for influencing the back-end activity • Use developments in other areas • Retrain of workforce allowing acceptance and perspectives for people decommissioning their own workspace • Collaborative work of different teams (technical, economics, etc.) in the organization and work together on a combined goal reaching • Use developments in other areas identifying synergies with other applications domains
Cross-cutting issues	• Match what is available and existing applications (Gap-analysis); Possible tool: survey • Refocus of the drives: to consider all the columns; focus on challenge, not the technology • Economic, safety, technological maturity • Clear definitions of what is being talked about (e.g. robotics/co-botics) • Keep the whole waste stream in mind (end-product) • Health and safety of workers • Promote modularity • Guidance and principals of usage of RRS • User RRS in the whole fuel cycle process (including new builds) • In nuclear economical focus, which is not the case in other areas • Bottom-up push development: end-user pushing developers (instead the other way around) • Playbook would be useful tool for member states (feasible) • Diversity in the field				

Annex B: Status of RRS in nuclear back-end applications

Note that these are examples provided by individual EGRRS participants and are not intended to be an exhaustive list of all available technologies and applications.

B.1 Mobile robots

The category "mobile robots" includes:

- Ground units that move using a variety of propulsion methods (wheels, tracks, legs, serpentines, wall-mounted suction cups);
- Aerial units (also known as unmanned aerial vehicles or drones), most commonly propelled by rotating blades; and
- Submersibles, commonly propelled by rotating blades or hydraulic jets.

This category is arguably the most commonly employed in back-end applications. Mobile robots are used to deliver equipment to perform specific tasks, such as cameras, sensors and/or detectors to perform inspection and characterisation activities; or task-specific end-effector systems (such as articulated arms fitted with grasping end effectors for moving material or obtaining samples).

Examples of mobile robot systems are provided below.

Use of Track Wheeled Robots at Duke Nuclear Power Plants:

Duke Energy procured commercially available PackBot and 710 Warrior units from iRobot (now Endeavor Robotics). The lightweight PackBot has been used for tactical operations, such as inspecting objects, and the 710 Warrior robot, which has a higher lift capacity and can travel up to 8 mph, is assigned to perform heavier functions, such as removing and replacing filters in the High Integrity Containers (HICs) located in the plant's four radioactive waste bunkers (Cato at al., 2013; Peterson and Monti, 2014).

The robots required a few modifications prior to being used. The primary change was equipping the robots so they could be used in areas of the facility that blocked radio signals. In this case, iRobot engineers equipped the 710 Warrior and PackBots with fibre spoolers that allowed operators to control them via a fibre optic tether rather than relying on radio frequencies. The utility selected the iRobot units in part because of their ease in learning how to use them with a video-game style control system.

Figure B.1. Endeavor Robotics 710 Warrior in Use at Robinson Nuclear Power Station

Use of Submersible Robots at DOE and Sellafield

The Remote Underwater Characterisation System (RUCS) is a small, remotely operated submersible vehicle intended to serve multiple purposes in underwater operations (see Figure B.2). It is based on the commercially available "Scallop" vehicle produced by Inuktun Services, Ltd., British Columbia, Canada (EPRI, 2015). The US Department of Energy modified the commercially available system to add radiation sensors and auto-depth control to the submersible, and to add vehicle orientation and depth monitoring at the operator control panel. RUCS is designed to provide visual and gamma-radiation characterisation, even in confined or limited-access areas. RUCS has been used to visually survey reactor canals and to gather characterisation data on the reactors and equipment on the floor of the canal. It is simple to deploy and its small size and manoeuvrability allowed it to operate beneath overhead structures and behind the reactors.

Figure B.2. Scallop Remotely Operated Underwater Vehicle (EPRI, 2015)

At the Sellafield nuclear site in the United Kingdom, a mini-submarine ROV was used to remotely monitor and retrieve samples from the bottom of the First Generation Magnox Storage Pond (FGMSP) (JFN, 2014). James Fisher Nuclear (JFN) worked with the site to plan, perform trial runs, and send a Video Ray Pro 4 ROV into the

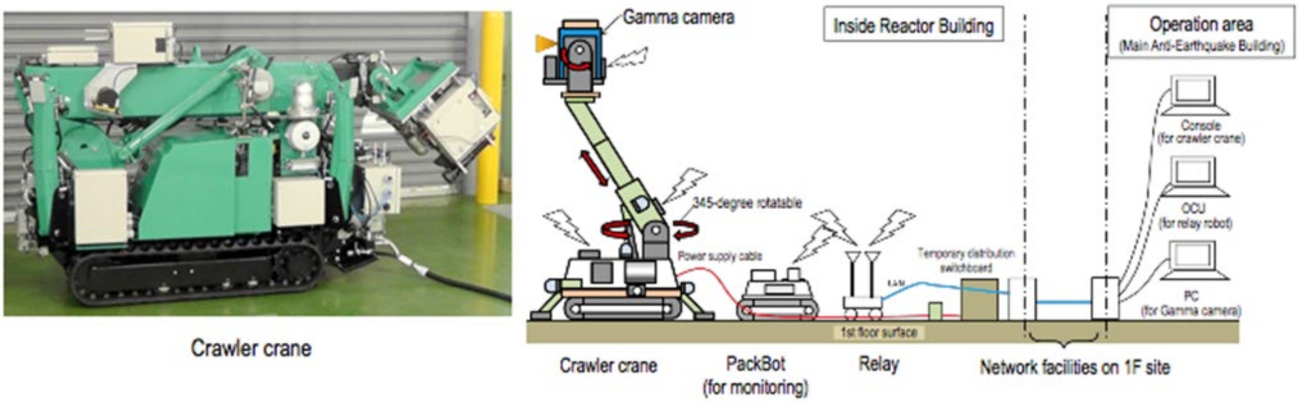
FGMSP for the monitoring and sample collection activities. This technology was taken from the oil and gas industry.

Magnox also mounted survey equipment on this technology and used this for the conduct of remote underwater surveys.

Crawler robot used at Fukushima Daiichi

Many robots have been successfully employed to perform a variety of inspection, sampling, and material handling functions at the Fukushima Daiichi site. One example is a remote-controlled crawler crane unit mounted with gamma cameras used to inspect areas significantly contributing to radiation dose rates (hot spots) on the 1st floor of the reactor building in Units 1 to 3 (FDADA, 2014).

Figure B.3. Crawler System Used for Dose Assessment at Fukushima Daiichi



Crawler crane

Wall-climbing robot for application of fixatives

Florida International University (FIU) conducted a demonstration at their mock hot cell of a remote fixative sprayer platform that was integrated onto an existing remote platform developed by International Climbing Machine (ICM) (see Figure B.4) (EPRI, 2015). This integrated platform has the capability of climbing up vertical surfaces. The integrated technology platform was successfully demonstrated to remotely enter into a mock hot cell facility and to spray a fixative on the ceiling, walls and floor surfaces. The spraying rate for the remote sprayer platform ranged from 3.4 to 4.3 square feet per minute (0.3 to 0.4 m^2/min) based on area covered, spraying time and product used. This is designed for hostile environments.

Figure B.4. ICM climbing machine spraying fixative

Source: EPRI (2015).

Sludge Crawling application for clean-up of nuclear ponds (Sellafield Ltd).

The Gerotto Bull has been modified to enable the final clean-up of the ponds before Sellafield can begin to dewater some of its legacy ponds. Decades of sludge remain on the floors of the ponds which may contain fuel elements or other large debris. The Bull has been modified to enable this sludge to be removed from the pond bed and to be contained, ready for downstream processing of the waste to commence.

Figure B.5. Gerotto Bull Sludge crawling robot

Sherpa, Hexapod Transporter Robot (experimental, tested in 2 nuclear plants)

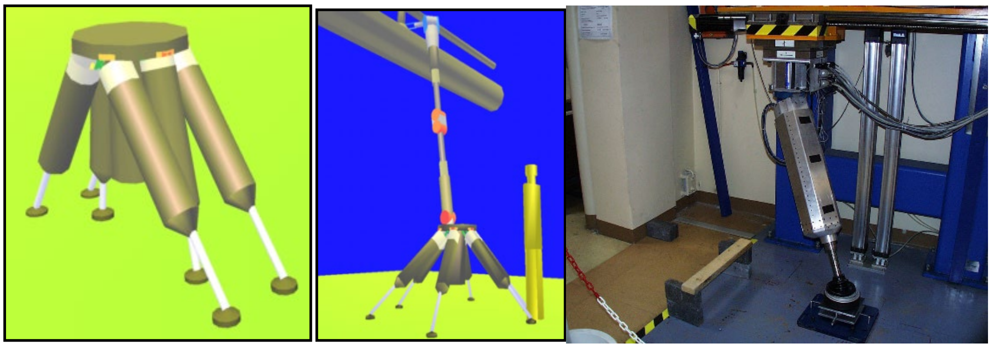
This project, partly financed by the European Teleman programme, was carried out between 1991 and 1994 and consisted in studying the efficiency of a legged transporter for the deployment of manipulator arms for maintenance tasks and the transport of protective elements in nuclear power plant buildings.

The machine was a hexapod platform with telescopic legs initially designed for the Odex 3 robot (Odetics, United States) and developed at the CEA with the creation of new walking algorithms exploiting reflex functions based on the exploitation of sensors integrated in the feet. The machine has become able to evolve by avoiding scattered obstacles, to cross narrow or elevated passages and finally to go up and down stairs. Mobility evaluation and load transport tests (200 kg in all circumstances) have been carried out in two nuclear power plants in France (Chooz) and Italy (Trino). During the second campaign, the staff members trained to pilot the robot carried out all the specified evolutions, including in degraded situations (oil on the ground, rubble, lighting defects, etc.).

Figure B.6. Sherpa transporter robot, in Chooz-B (1993, left) and Trino (1994, right)

This programme was followed by a design phase by the CEA (with the support of EDF and TECHNICATOME) of a new hexapod with innovative telescopic legs with a compact synchronised mechanism and a light hyperstatic structure, with a reduced size from 0.85 to 0.65 m, an equivalent transport capacity and a speed 2.5 times higher (12 m/min). A complete leg was successfully tested on a locomotion bench in 1998, including endurance tests. This project, which was to lead to tests by the members of the consortium in various maintenance or post-incident situations, did not materialise however.

Figure B.7. Sherpa 2 transporter robot (left); with a telescopic carrier (centre); its innovative synchronised telescopic leg on a test-rig (1998, right)



B.2 Articulated robots

Articulated robots have widespread use in industrial applications and many are commercially available. These units are often mounted to stationary or mobile platforms. They may be used directly to manipulate material or deliver task-specific end effectors. Examples of articulated robots are provided below.

MAESTRO telerobot (CEA-CYBERNETIX)

In collaboration with the CEA (Commissariat à l'energie atomique et aux énergies alternatives), Cybernetix has designed various 'slave' arms for telerobotic systems such as the electro-hydraulic MAESTRO, which has been used for applications in France and other countries (EPRI, 2016). The MAESTRO telerobot, shown in Figure B.8, is composed of the slave arm, the master arm MAT6D and a toolbox of various components that can be assembled to perform virtually any telerobotic task in a nuclear environment through its dual master-slave force feedback/robotic modes.

Figure B.8. The MAESTRO telerobot: Left, MAESTRO Slave arm; Right, MAT6D Master arm (EPRI, 2016)

The MAESTRO telerobot includes:

- A 2.34 m long, 60 kg payload capacity, torque controlled, slave hydraulic manipulator with 6 degrees of freedom, and a tool changer;
- An embedded hydraulic power pack;
- An embedded electronic controller;
- A control system with a wide range of control modes, including joint torque control on both arms, gravity compensation of the arms, force feedback master-slave coupling mode, Cartesian robotic mode, virtual guide mode, virtual reality (VR) training system with force feedback;

- A complete set of tools for dismantling and maintenance (nibbler, gamma camera, drill, laser torch, offset screwdriver, video camera, IF104 radiation probe, screwdriver, disk grinder, hydraulic shears, alternating saw);
- Two pan and tilt cameras with a specific controller to automatically follow the tools;
- A MAT6D (CEA -Haption^{TM}) force feedback master arm.

Large components at the Belgian research reactor BR3, including the reactor pressure vessel (RPV) head and bottom, pressuriser and steam generator, were segmented using high pressure water jet cutting deployed by a MAESTRO manipulator.

MAESTRO in the hot-cell 414 of the Marcoule pilot plant

The DEM APM C414 project aimed to demonstrate the reliability of the MAESTRO dismantling system under industrial conditions. It allowed the dismantling of centrifuges, a pulsed filter, settling pots, dosing wheels, flow pots, active and/or inactive effluent circuits.

Figure B.9. MAESTRO in the hot-cell 414 of the Marcoule pilot plant

Summary of operations carried out from 23/11/2015 to 24/05/2017, i.e. 18 months: 3 163 kg of process waste packaged in 43 baskets out of a total of 3 562 kg (process waste – historical) in 52 baskets.

MAESTRO in dissolver A of the Plutonium Plant n°1 of Marcoule

The CEA has signed a contract with an industrial company (ONET TECHNOLOGIE) which is responsible for supplying the MAESTRO process as well as its operation and maintenance. The dissolver is dismantled according to the cuttings: chimney, piping, upper internals, dome and upper shell, cutting of the lower internals, the basket, the dished bottom, the lower shell and the fuel drop tube.

Figure B.10. MAESTRO in dissolver A of the Plutonium Plant n°1 of Marcoule

The MAESTRO telerobot was used over a period of 30 months from the end of 2015 to June 2018 for the first phase, the cutting of dissolver A and the recovery of deposits and waste: 11 tonne of metals and 40 litres of deposits packaged in eighty 0.5 litre jars.

ARTISAN Robotic arm used at West Valley

West Valley Environmental Services, in partnership with Nuvision Engineering, Inc., developed a robotic arm (ARTISAN) to remove thousands of feet of small diameter piping (5 cm to 20 cm), and structural steel (up to 20 cm) from a chemical processing cell (NEA, 2011). The robotic arm was fitted with a mechanical shear for 5 cm piping, a band saw for 15 cm piping, and a circular saw for structural steel. The arm was fitted with a remotely operated wrench to allow disassembly and removal of bolted tanks. The ARTISAN arm performed beyond expectations, and substantially reduced personnel radiation exposure during the dismantling operation.

There may be a possible use for this manipulator for removal and cutting of piping, although the system deployed at West Valley had limited capabilities for larger diameter piping. The equipment may be useful to crimp or shear the piping for increased contamination control and could potentially be deployed by a mobile robot to limit set up.

B.3 Task-specific end effectors

Task-specific end effectors are typically mounted to stationary or mobile platforms (see examples in previous sections). This includes automated or remotely controlled units for material manipulation, welding, cutting, decontamination, application of fixatives, etc.

Automated spent fuel canister welding system at Zion

Zion Station purchased and deployed an automated remote welding system to apply closure welds and perform non-destructive inspections of the fuel canisters after loading to reduce radiological exposure to its workers (Daly, 2013). The system comprised a weld head and camera mounted to a remote-controlled articulated arm. This first-of-a-kind robotic welding system was used on both fuel and Greater-Than-Class C canisters and had the capability to remotely perform non-destructive testing of the welds. In general, some type of automated nuclear canister welding system has been implemented at more than 10 nuclear power plant sites that are using remote welding as one way to minimise workers' exposure to radiation.

Risk reduction of Glovebox operations at Sellafield ltd.

Sellafield Ltd possess a large number and variety of gloveboxes used to contain and carry out tasks with nuclear materials. Manual operations in gloveboxes carry a considerable risk to operators and Sellafield Ltd therefore aspire to remove the need for operators to undertake manual operations in gloveboxes. A prime candidate technology to achieve this is the use of a robotic manipulator employing techniques such as haptics, VR and AI that will interface with a glovebox and can augment the operator thereby remove them from the immediate risks. Although complete elimination of manual operations is unlikely to be achieved in the short term and effort is focused on achieving a significant risk reduction to operators in the short term.

Figure B.11. Robotic manipulators at Sellafield

B.4 Control ssystems for remote operations

Systems that are typically manually operated can be readily converted to remote operation, and there are many examples of this practice for back-end applications. They include equipment such as saws, scabblers, hydraulic rams, decontamination baths, and waste conditioning or treatment systems. An example of equipment converted for remote operations is provided below.

Reactor vessel internals segmentation at Jose Cabrera

Segmentation of reactor internals components is performed underwater, typically in the reactor cavity or spent fuel pool (SFP). At Jose Cabrera, segmentation was performed on top of a stand over a dedicated turntable resting on its floor. The placement and control of the different cutting and handling tools was performed manually by operators from a purposely built bridge crane over the SFP, riding on the same rails as the old bridge crane, and making use of the two updated reactor building cranes.

The cutting tools used in the reactor vessel internals segmentation were a band saw, a disc saw, a drill tool and shear tools. All tools were hydraulically powered and controlled, and could be easily reconfigured, e.g. to change cut direction. They were manually controlled by the operators on the bridge, via control boxes that monitored and modified parameters such as cutting speed and force.

Lifting and handling of cutting tools and segmented pieces was performed under manual operator control from the bridge, with the help of both the bridge and reactor building cranes. Standard pneumatic and hydraulic powered clamp type tools were used to lift the cut pieces, in combination with bayonet connected extension poles, while heavy pieces (up to 5 tonnes) were handled by heavy duty mechanical grippers.

Figure B.12. Remotely operated bandsaw for internals segmentation at Jose Cabrera

B.5 Conveyors, lifting systems and mobile platforms

This category includes systems for manipulating material and staging equipment. It includes cranes and winches that have been configured for mobile operation, conveyor systems for moving material through an automated process and large mobile platform systems designed to deliver and stage other remotely operated systems for deployment. Examples of platform systems are provided below.

Mobile Tool Platform used at Fukushima Daiichi and Chernobyl

PAR Systems, LLC developed the TensileTruss™ technology that serves as a long reach, stable platform for remotely operated tools. The TensileTruss is composed of two triangular shaped platforms, upper and lower, connected by six wire ropes and positioned by six hoists (which is an inverted Stewart Platform). The hoists raise and lower the platform and due to the geometry and rope tension due to the mass of the lower platform, the lower platform can sustain significant horizontal loads and reactive torque generated by dismantling tools (i.e. acts as a rigid truss).This stable lower platform provides an ideal delivery system for remote tooling where a telescoping mast is impractical due to a long reach and high tooling loading is expected, which is the case at the Chernobyl Nuclear Power Plant.

PAR Systems provided their patented TensileTruss technology at Chernobyl as the Trolley deployed Mobile Tool Platform, along with a complex, 50 Tonne robotic crane. The crane and TensileTruss system comprise the Main Cranes System for the New Safe Confinement now in place over Unit 4 of Chernobyl in Ukraine and will be used in the safe dismantling of the Sarcophagus and the destroyed reactor using tools such as a remotely operated high capacity arm and high capacity shears.. The MTP can handle 1.5 tonnes (1.7 tons) of side load capacity at an extension of 44 metres (144 feet) without sway, which would be impossible to achieve with a standard hoist. The designallows for remote work to be completed that is otherwise difficult due to the elevation and radioactive environment. The total vertical extension of the TensileTruss lower platform is 70 metres (230 feet), enabling it to reach from just below the ceiling all the way to the ground (PaR, 2015).

The TensileTruss technology was also provided by PAR to support the clean-up activities at Unit 3 of the Fukushima Daiichi nuclear site in Japan. The Fukushima TensileTruss was successfully used to remove spent fuel from Unit 3 following the tsunami and subsequent hydrogen explosion. PAR's Fukushima system is a rolling gantry system, which has four lifting devices: two 5T auxiliary hoists, one 1.5T fuel handling mast, and one 1.5T tensile truss, equipped with dual hydraulic manipulators supplied by Westinghouse.

Figure B.13. Fukushima overall gantry (Owen, 2014)

Work platform used at Chicago Pile 5 Reactor

A Dual Arm Work Platform (DAWP) was used to perform mechanical dismantling of the radioactive reactor and bio-shield structures (EPRI, 2015). The DAWP manipulated standard, commercially available tools (i.e. circular saws, jackhammers) using two Schilling Titan III six degrees of freedom hydraulic, tele-operated manipulator arms controlled from a remote location. The two arms were mounted to a steel work platform designed to hold the associated tooling, utilities and cameras supporting the operation of the manipulator arms. The DAWP was provided by a consortium of US national laboratories and industry manufacturers. Individual components and subassemblies were purchased from or provided by Schilling Robotics Systems, RedZone Robotics, Inc., ORNL and INEEL. The robotic arms utilised were Titan III manipulator arms made from titanium and stainless steel and were supplied by Schilling Robotics.

The DAWP provided for control of five electrical and two hydraulic tools, had a remote viewing system, a lighting system, and a tool control system. The DAWP was designed to minimise the on-board electronics and hydraulic valves for radiation tolerance, and to facilitate decontamination and so a relatively large diameter tether linked the platform to the hydraulics source and control system.

The control hardware rack and the hydraulic power unit (HPU) were mounted in the basement away from the radiation and contamination hazards expected in the reactor shell. The DAWP operator control station consisted of a video console, control chair, master controller station and the virtual window stereo viewing system.

Figure B.14. DAWP Used for material handling in a high radiation area

B.6 Wireless data transfer and control systems

Remote operations are greatly enhanced if physical connections (umbilicals, tethers, etc.) are not required for data transfer and control. Many recently developed systems include capabilities for wireless control and retrofitting existing remotely operated systems is an area to be developed. Wireless transmission inside the typically robust concrete structures present in nuclear facilities continues to be a challenge. An example of a system configured for wireless control is provided below.

Autonomous Radiological Characterisation System

EPRI has assembled and demonstrated an autonomous system for radiological characterisation of large land areas and open floor areas during decommissioning. The system comprises a commercially available wheeled robot (Adept MobileRobots Seekur Jr. platform), a commercially available sodium iodide detector system with a multichannel analyser, and a custom-designed control and navigation system. The assembled system includes a LiDAR unit for navigation and obstacle avoidance, and an internally installed on-board computer that performs all of its necessary computing tasks, such as:

(1) localisation and navigation,

(2) measurement device communication,

(3) data collection, and

(4) data storage.

The on-board computer can be remotely accessed through a Local Area Network (LAN) and Wi-Fi access point that is attached to the platform.

The system was successfully demonstrated at the shutdown Kewaunee Nuclear Power Station.

Figure B.15. Prototype of autonomous radiological characterisation vehicle

Multipurpose wireless modular ground robots

RoboDecom is an industrial innovation project co-financed by Link and Allinvent, Norwegian robotics companies, and the Research Council of Norway, led by the Norwegian Institute for Energy Technology (IFE) and including Sintef (Norway) as well as Createc, Tecnubel and Magics as associated international partners. RoboDecom is developing a multipurpose wireless modular system to support nuclear decommissioning projects based on the integration of existing unmanned ground vehicles (UGVs) with advanced 3-D radiological scanning systems (by Createc – see Figure B.20), software modules related to robot mission planning and control and 3-D spatial data visualisation, as well as other end effectors (e.g. a drilling system). The RoboDecom system takes advantage of various UGV platforms including the world’s first robotic ceiling drilling system by nLink, quadrupeds (in this case Spot by Boston Dynamics, now part of Hyundai) and four-wheel systems (in this case Jackal by Clearpath). In RoboDecom, the modular nLink platform provides functionalities for deploying sensors and tools across industrial installations, including capabilities for positioning payloads high above the floor level, while quadrupeds and four-wheel units (in this case Spot and Jackal) provide access to areas that are difficult to access by tracked vehicles and serve as mobile hubs for wireless communication.

The RoboDecom system aims at combining important capabilities identified as key industry needs related to nuclear robotics in and integrated system. These capabilities are provided by a collaboration of UGV platforms as follows:

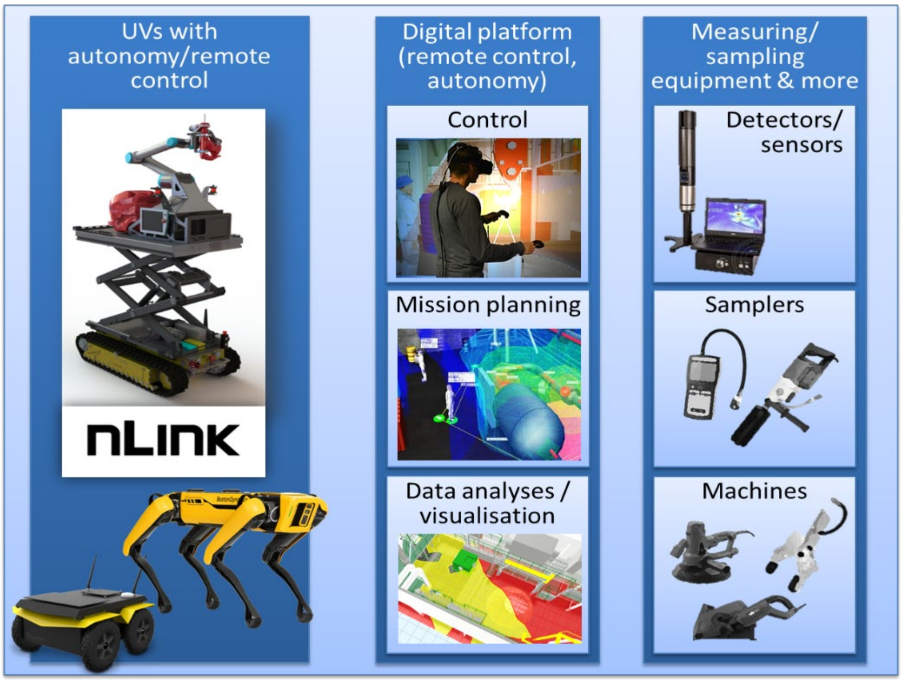
nLink UGV system:

- Smooth movement providing capabilities for positioning scanners in a constant plane without the need for stabilisers across large industrial floors;
- High reach provided by a scissor lift/telescopic system;
- Capabilities for flexible/dynamic and precise deployment of payloads using robotic arms and precise positioning systems, including a total station;
- Capabilities for deploying both tools and sensors;
- Wireless connection using a modern communication topology;
- Integration with a Building Information Management (BIM) system providing capabilities for positioning and managing data within a BIM approach;
- Integration with real-time 3-D radiological modelling and visualisation allowing a hazard and DQO (Data Quality Objectives) informed mission control.

Quadrupeds and four-wheel units:

- Capabilities for deploying sensors and mobile communication hubs across large areas, including areas that are, typically, hard to access by conventional tracked robots and larger units with decent payload capacity (like the nLink UGV system).

Figure B.16. The RoboDecom multipurpose wireless modular robot system.



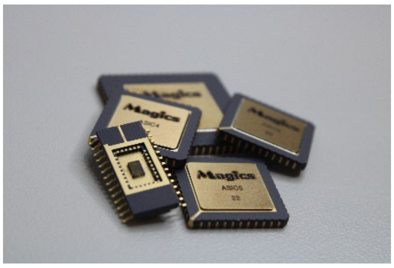
The first RoboDecom prototype will be developed in 2021 and demonstrated next in 2022. In the slightly longer term, the RoboDecom system will be equipped with machine learning based and other algorithms allowing autonomous navigation and detection of hazardous conditions.

B.7 Sensing and control platform for harsh environments.

Semiconductors have always been the carrier of technology advancements. However, the abundance of these technologies has led to manually operated robotics, driven by big cables, leading to robotics and manipulators that are difficult to operate and maintain.

In that context, Magics has developed a motion control chipset (Figure B.17) for closed loop sensing applications. The system is radiation hardened and can survive accumulated doses of more the 1 Mgy.

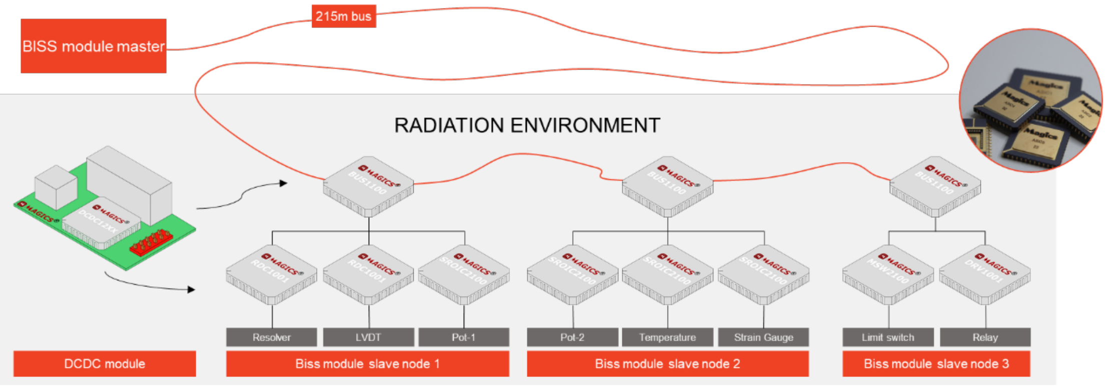
Figure B.17. Packaged motion control chips.



The first use cases were in the remote handling system at the world’s largest experimental nuclear fusion reactor to automate maintenance and inspection operations. Next, in the nuclear decommissioning industry, the technology delivered significant time and cost efficiencies.

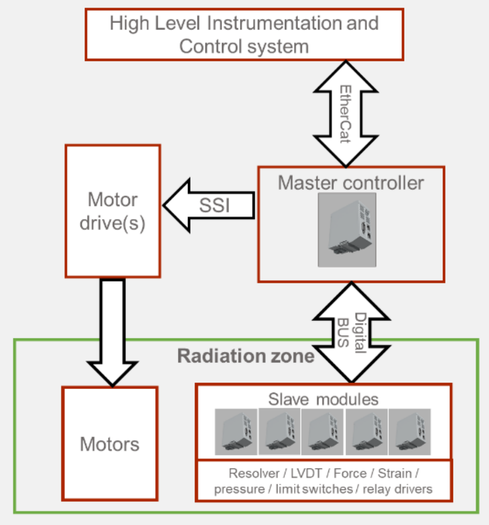
The system consists of a Bus controller that has a deterministic communication protocol embedded. This makes it possible to receive exact timing information from all the sensors in the network. The Bus controller chip can connect with 3 Serial Peripheral Interface (SPI) slave Application-Specific Integrated Circuits (ASIC). These slave ASICs can connect Resolvers, linear variable differential transformers (LVDT), strain gauges, force sensors, pressure sensors, etc. On top of that they can read out limit switches or drives relays for motion control. Power supplies are included in the system as well, to foresee local distributed DC power distribution. A master module can receive and send digital data from a 215-metre distance from a control cubicle.

Figure B.18. Overview of ASIC functions and motion system.



The ASIC can be used stand-alone or integrated in master-slave modules that can be plugged into an electrical cabinet as shown in Figure B.19.

Figure B.19. Overview of ASIC functions and motion system.



The master controller can communicate with a higher level control system used by an integrated system. An synchronous serial interface (SSI) is foreseen to communicate with existing motor drivers. In the radiation environment, sensors or relay drivers can be connected.

The electronic platform and unique semiconductors technology bring new levels of automation to the nuclear industry. The modules offer an easy way towards standardisation of robotic fleets and manipulators and removes the need for customisation. The control system enables robust and reliable controls of robotics. The local digital control allows for easy multiplication of sensor interfaces, which makes it possible to increase safety integrity levels (SIL) of remotely handled systems.

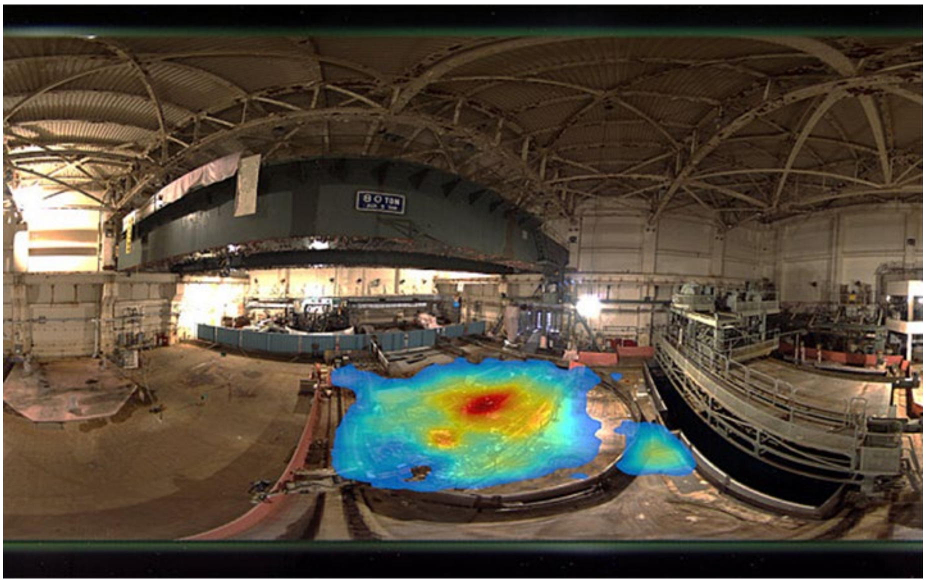
B.8 Miscellaneous specialty systems

This general and broad category includes technologies that do not fit neatly into the categories discussed above. Examples of such systems are provided below.

N-Visage gamma camera used at Fukushima Daiichi for radiological characterisation

Createc designed a gamma camera system (N-Visage) that could be mounted onto remote-controlled drones and caterpillar-tracked robots for the visualisation of radiation inside the Fukushima Daiichi reactor buildings (REACT, 2017). The system is able to create a real-time, three-dimensional image of the area being surveyed and identify hot spots of radioactivity. Figure B.20 shows one of the hot spots inside a reactor building.

Figure B.20. Image of a hot spot mapped inside a Fukushima reactor (REACT, 2017)



The N-Visage™ software system takes laser scanning and gamma camera radiation data and constructs a 3-D map of where the radioactive sources are potentially located within a building (REACT, 2017).

The N-Visage™ gamma camera has also been used with a laser scanner modelling system at the United Kingdom Sellafield Separation Plant (REACT, 2017) to characterise a cell and its contents. REACT Engineering Ltd and Multipass 3-D Laser Scans Ltd carried out the laser scanning using a FARO LS 880 laser scanner that precisely mapped the contents of the cell. The data obtained was used to create 3-D model images of the shear cell integrated with the data from the gamma scanner. This is an example of work that can be used to remotely survey and construct 3-D files for use in decommissioning planning and geostatistical evaluations of the data.

Autonomous exploration and mapping in nuclear power plants

For the (semi-) autonomous decontamination of building structures in nuclear power plants, the detection of unknown environments, as well as radiation measurement, is important. For this purpose, a multisensory, agile robot system, that drives autonomously through the plant areas or buildings, was developed and expanded by the Institute of Technology and Management in Construction at Karlsruhe Institute of Technology (KIT-TMB). In this platform, the FARO Focus S150 integrated into software is used for laser scanning, which can receive and process the scan data to a point cloud data automatically. Furthermore, 2-D maps, which are created from the point cloud, are used for localisation in autonomous exploration. For autonomous radiation measurement, a scintillator probe for local dose rate measurement is used. The purpose is to investigate whether the distribution of the local dose rate is homogeneous so that hot spots can be found.

The platform can also be remotely controlled and tele-operated by using the developed interface from a co-operated institute at KIT.

Figure B.21. Mobile robot platform for the environment exploration and radiation measurement

Mobile robot platform for automation of decontamination and subsequent (clearance) measurement

At the Institute for Technology and Management in Construction (“KIT-TMB”), the focus is on the development of automated solutions for the decontamination and for the clearance measurement of near-surface contaminations for nuclear power plants. Research is being conducted at TMB on the development of practical robot platforms that optimally support the user in the decommissioning process.

KIT-TMB uses a mobile elevating working platform with two tools as a robot platform. With the first tool, an automated milling tool, wall areas within a plant area or building where the thresholds for surface contamination have been exceeded can be specifically decontaminated. The second tool, an automated contamination array, measures the surface activity on the wall areas and verifies compliance with the thresholds. To do this, the tool on the boom is changed and the second tool can be mounted. For the automation of the work and a practicable exchange of the tools, an interface on the cantilever was developed. In addition to these two tools, other tools for decontamination are conceivable.

Figure B.22. Robot platform with milling tool and contamination array

Spent fuel check vehicle

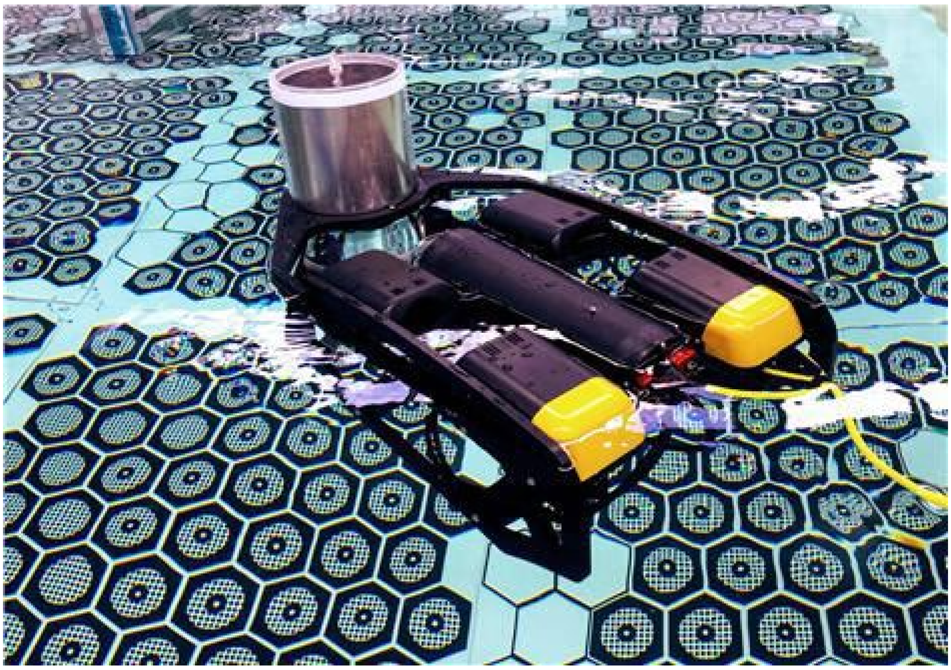
Korea Atomic Energy Research Institute's (KAERI's) newly developed spent fuel check vehicle (SCV) was included in the "Small Unmanned Surface Vehicle" section of the "IAEA Robotics Challenge 2017," held in Australia.

KAERI's SCV can travel at 30 centimetres per second, faster than other similar machines, and can automatically analyse spent fuel. Its user-friendly user-interface (UI) makes it easy to manoeuvre by remote control. Its compact size, weighing less than 11 kilograms, allows it to be carried on a plane. The SCV can be assembled in under five minutes, while minimised areas of outside exposure allow fast clean-up.

The SCV's final evaluation will take place inside an actual nuclear power plant. Once it passes the technological test, the SCV will be prepared for mass production and export, with numbers in accordance with the IAEA's request. It is the first time that the IAEA has been involved in developing a robot to check the environmental impact of nuclear energy.

So far, the IAEA has been sending experts to inspect spent nuclear fuel in underwater storage and radioactive waste in containers on land. But the organisation has been aware that areas that can be difficult to access, or with elevated radiation levels, would be best inspected by robots. A handheld optical instrument called an Improved Cerenkov Viewing Device (ICVD) is used to confirm the presence of spent fuel stored underwater.

Figure B.23. KAERI spent fuel check vehicle



Available at: www.youtube.com/watch?v=IAFL-Ug8nFY

LAROB: Laser-guided underwater mobile robot for reactor vessel inspection

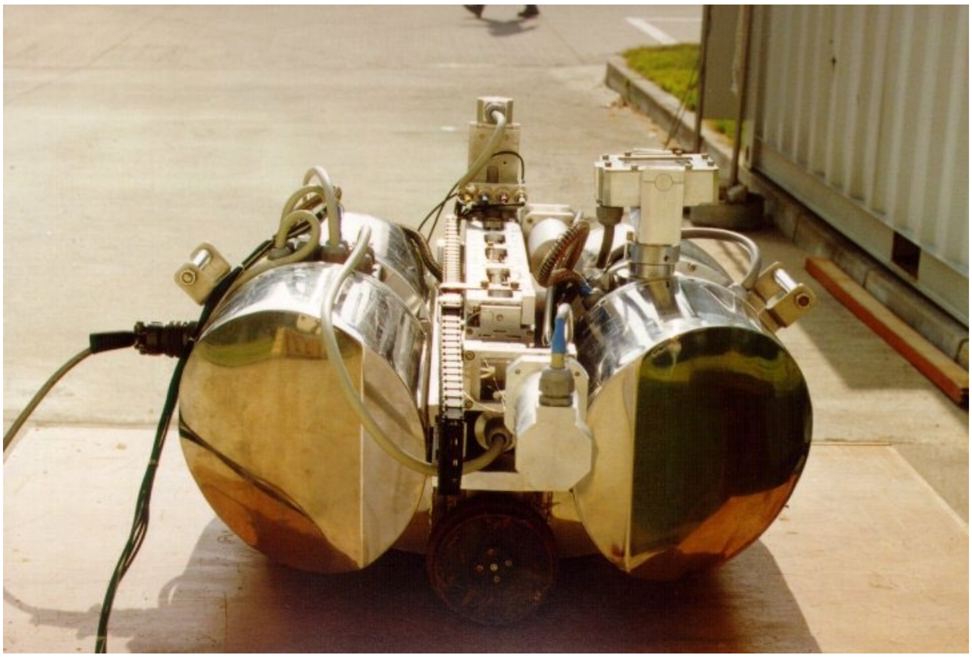
LAROB (depicted in Figure B.24) is a submarine-type mobile robot whose weight is approximately 40 kg but drops to zero in water with the aid of floats. Most of the reactor pressure vessel in a pressurised water reactor (PWR) is composed of carbon steel and is clothed inside with austenitic stainless steel. To climb the vertical wall of the vessel, LAROB has four magnetic wheels. The ring-shaped magnet has N and S poles on each side of the magnet. Pure steel circular plates are attached on each side of the magnet to maximise the attraction force to the vertical wall. Smooth rubber is clothed around the magnet to prevent slippage on the vertical wall. Among four magnetic wheels, two are caster wheels and the other two are driven by dc servo motors so that the robot can move in any direction on the vertical inner wall of the reactor vessel. The robot can control the linear velocity and angular velocity by the sum and difference of the velocities of the left and right driving wheels.

Both the front and rear caster wheels are mounted on the parallelogram links with the robot body plate. It keeps the robot body parallel to the wall, even though the wall is cylindrical. The caster wheel frame can move only up and down, keeping the posture parallel to the robot body frame.

The robot also has a light and long manipulator, and the ultrasonic probes are attached to its end effector. The manipulator has five degrees of freedom, which are slide, tilt, rotation, four consecutive translations and probe rotation. Slide is the relative motion of the frame {M1} in the x-axis direction {ROB}, whereas tilt is the small amount of rotational motion of the frame {M2} about the z-axis {M2}. Rotation is the rotational motion of the frame {M3} about the z-axis {M3}. The manipulator can reach up to 100 cm using four consecutive translation links, which are driven by a wire train. It is not easy to design a long-reach manipulator kinematically, as it must be light and non-bulky in order to be mounted on a small mobile robot. The probe assembly can be rotated about the z-axis of frame M5 and can move up against the spring tension, and the ultrasonic sensor can be tilted to closely contact the reactor vessel wall surface. The camera and lamp are mounted on the robot, and a visual image from the camera is transmitted to the main control station.

The robot is induced by the laser pointer, which is fixed in the middle of the crossbeam across the reactor upper flange. The laser pointer emits a laser beam to the next position for the robot to move. The robot, with the position sensitive detector on its back, detects the deviation of the laser beam spot from the centre of the position sensitive detector, and moves in the appropriate direction to make this deviation zero. The laser pointing device is a kind of pan-tilt device upon which the diode laser is mounted.

Figure B.24. KAERI LAROB Underwater inspection system

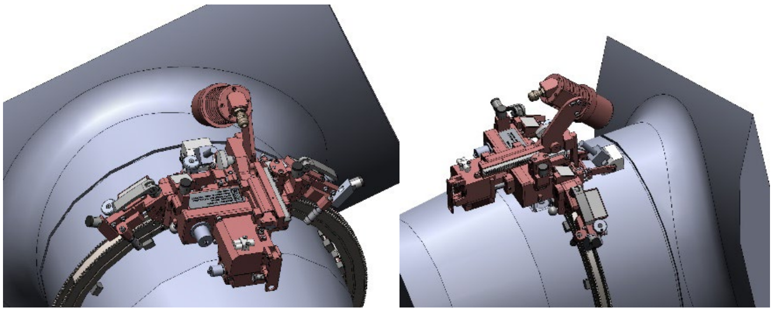


Robot for non-destructive inspection of angular welded joints of reactor pipes

The scanning system provides the possibility of television and ultrasonic testing of angular welded joints of the main circulation pipeline nozzles. It supports:

- Inspection of angle welded joints using technical vision technologies and ultrasonic flaw detection.
- Control of angular welded joints of nozzles with outer diameter of 70 mm, 121 mm, 192 mm, 200 mm, 252 mm, 280 mm, 400 mm, 462 mm, the possibility of further addapting the system for other diameters.

Figure B.25. Robot for non-destructive inspection of angular welded joints



Robot for non-destructive inspection the cover of the PWR reactor unit

The manipulation system (MS) “Control-VB” is designed for pre-operational and operational control of the metal of the nozzles of the control and protection system (SUZ) and intrareactor control (VRK) of the upper unit of the VVER-1200 reactor unit.

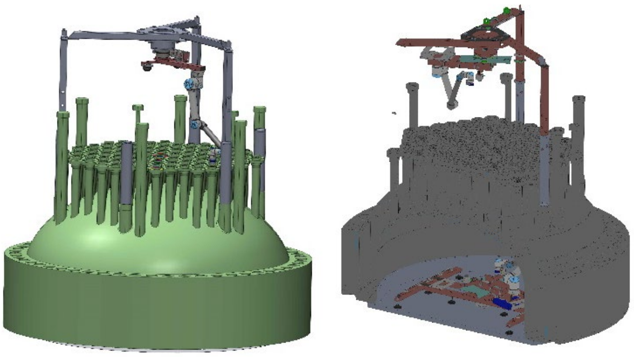
When developing design and software solutions for the manipulation system, special attention was paid to the fulfilment of such customer requirements as ensuring high accuracy of the MS (maximum positioning error of the equipment – no more than 2 mm) and the ability of the system to function for a long time in extreme conditions of the nuclear power plant (not less than 2 000 hours). In addition, the system should be as safe as possible for the work of the station’s maintenance personnel and ensure that control operations are carried out in the shortest possible time. MS includes a manipulator, lower frame, upper frame, control unit, computer, replaceable modules of non-destructive testing and a contact fluid supply device. The manipulator has five rotational degrees of freedom, and a replaceable module of non-destructive testing is attached to the output link of the manipulator.

The main types of control operations using the manipulation system “Control-WB”:

- ultrasonic testing (ULTRASIC) of welded joints and base metal of the nozzles of the SUZ and VRK from the outside of the nozzles, the cover of the upper block around the nozzles according to the thickness of the lid, as well as surfacing on the lower ends of the nozzles of the SUZ and VRK and the sealing surfaces of the nozzles of the SUZ and VRK for detachment from the base metal of the nozzles;
- eddy current control (VTK) of the shirts of the nozzles of the SUZ and VRK along the entire length and the internal surfacing of the upper block cover, including the lid flange;
- television control (TVK) of welded joints and internal surfaces of pipes and shirts of nozzles of SUZ and VRK with internal surfacing of the cover of the upper block, flange of the WB cover;

The MS uses a modular scheme for installing scanning devices. For television control of the flange surface of the upper unit cover, a flange television control module is used, which is a separate mobile module and, unlike other modules that are installed on the manipulator, is placed directly on the controlled flange surface of the upper block cover on a magnetic suspension.

Figure B.26. Robot for non-destructive inspection the cover of the PWR reactor unit



<u>Emergency response robot to work in areas with high radiation levels, localise gamma radiation sources in hazard areas.</u>

Robotic complex RTK-08 is designed to eliminate the consequences of emergency situations of a technical nature and work in areas with high levels of radiation, localisation of gamma radiation sources in hard-to-reach areas, in industrial and residential premises, transport facilities, etc. It can:

- perform liquidation of the consequences of emergency situations of a technogenic character;
- work in areas with high levels of radiation;
- localise gamma radiation sources in hard-to-reach areas, in industrial and residential premises, transport facilities, etc.

Figure B.27. Emergency response robot

Electrical master-slave remotely handled waste reconditioning

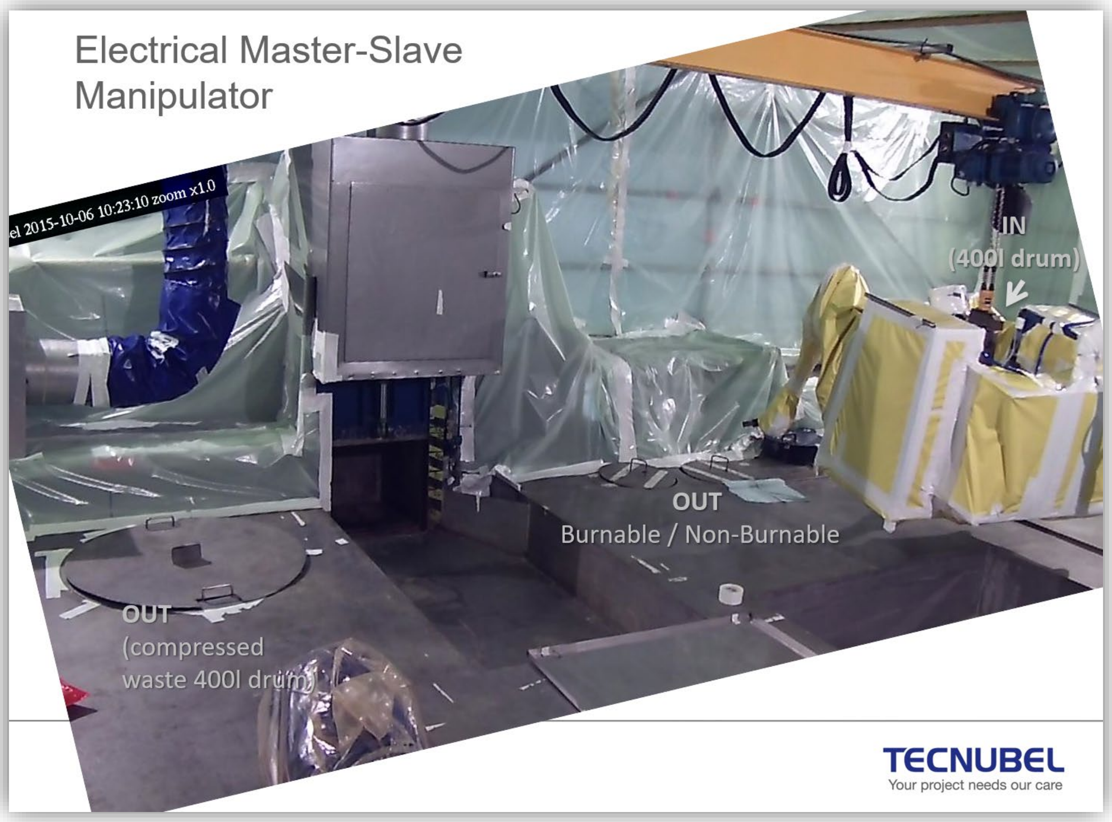
In order to prevent radiation dose accumulation by workers, an electrical master-slave (EMS) system was developed by ENGIE for the remote handling and conditioning of radioactive waste. This modular and mobile EMS has now been used in Belgium and Germany for several years.

In this solution, remotely controlled double EMS arms are installed in a modular double tent confinement, in which also a compactor (100 tonne) can be installed. The tent is kept in slight negative pressure and is equipped with its own air filtration.

The EMS unit is mounted on a mobile bridge, with the ability to move it in all directions, rotate it and adjust its height (see Figure B.28).

A working platform will be provided, under which the containers with radioactive waste can be placed for emptying remotely. Positions are also provided for empty drums to drop the sorted and characterised and possibly compacted waste.

Figure B.28. EMS, wrapped in yellow foil, on mobile bridge above the working platform in a double tent confinement, equipped with a 100 tonne press (photo ENGIE Tihange Nuclear Power Plant)



The entire system is compact and modular, and can be transported via 20’ ISO containers (see Figures B.29 and B.30).

The controls through master arms are set up in a 20’ ISO container outside the controlled area. Power and control units are also set up outside that zone. Figure B.31 provides the principal lay-out.

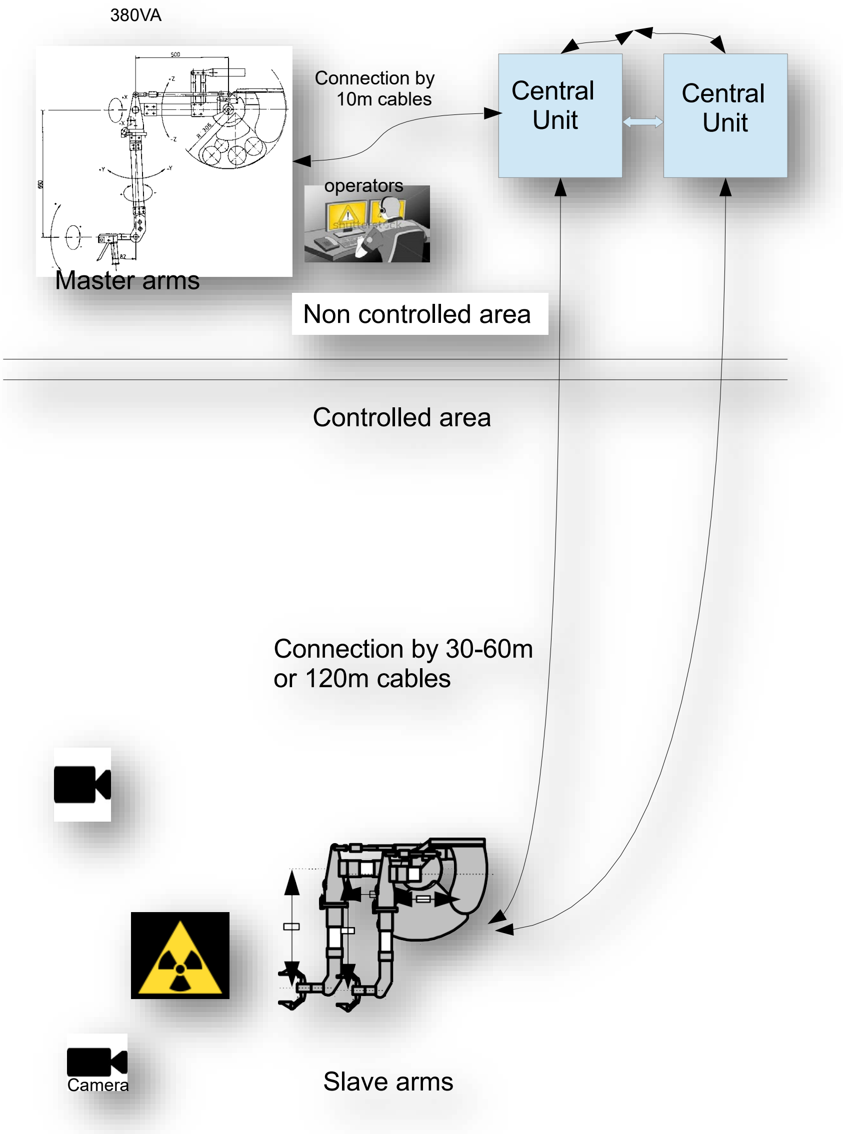
The equipment is a combination of robust and reliable off-the-shelf equipment, which is easy to assemble and disassemble, and low maintenance.

Figure B.29. Master arms installed in 20’ ISO container (see next figure)

Figure B.30. 20’ ISO container, or control unit equipped with master arms and power supply

The EMS are always properly packed in the controlled area to protect them from contamination. Some of the tools which come into contact with the contaminations, for example the grippers, are sometimes difficult to decontaminate and remain with the customer or are considered secondary waste.

Figure B.31. EMS principal lay-out



RX TAO telerobot (CEA-Orano)

The RX TAO is a family of force feedback telerobots whose particularity is that the slave arm is an industrial robot from the Stäubli™-RX range equipped with a 6-axis force sensor. The generic TAO software thus authorises the force feedback slave master mode by coupling to a master arm of the Haption™ range (MAT6D / Virtuose 6D) and make it possible to benefit from sophisticated assistances such as virtual mechanisms or guides and an automatic robot mode. Its development was achieved by CEA in close collaboration with the operator Orano La Hague. The arm’s robustness has enabled it to be used since 2005 for a series of maintenance campaigns on the dissolver wheel at the Orano La Hague fuel reprocessing plant.

The specifications issued by AREVA Nuclear Cycle (now Orano) were for an industrial slave arm resistant to radiation (at least up to 10^4 Gy), decontaminable and able to be either remotely controlled with force feedback or used in robot mode (programmed). The Stäubli RX family of robots, known for high reliability, was selected and adapted to the specifications of the nuclear environment (connectors, decontamination). The CEA has therefore carried out important R&D work to make the arm tolerant to radiation and to allow master-slave remote handling with force feedback. Radiation tolerant absolute position resolver type joint sensors have been selected and implemented.

A radiation tolerant version of the original ATI Industrial Automation 6-axis end effector force transducer and a high-speed radiation tolerant signal multiplexer were specifically developed by CEA to significantly reduce the size of the RX arm umbilical compared to its industrial version (ROC). This allows the arm to pass through the cell walls of the reprocessing plant (Ø 36 mm) and facilitates the safe movement of the arm on the carrier systems. The CEA has also developed a computer-aided tele-operation control system based on its generic TAO2000 software running in Cartesian co-ordinates and offering advanced functions, such as master/slave mode with force feedback and robotic trajectory planning.

Today, Orano possesses a wide range of industrial robots that can be used remotely (Figure B.32) and can be quickly adapted to different types of intervention. The necessary work is carried out by Temis, an Orano subsidiary.

Figure B.32. Stäubli™ RX90, 130 and 170 range of radiation tolerant industrial robots implemented by AREVA NC (Orano La Hague)

Since 2005, at least one or two maintenance campaigns per year have been achieved with the RX170-TAO on the two UP3 and UP2-800 installations at La Hague. They concern either the maintenance of the dissolution wheel rollers carried out in the tele-operation mode with force feedback, or a cleaning operation of the inter-tank space of the dissolution wheel carried out in automatic robot mode (Figures B.33 and B.34).

The technical interest of the force feedback master-slave mode for maintenance operations on the dissolver wheel, an essential element of the La Hague reprocessing plant, is to guarantee:

- safe handling of the 60 kg roller;
- positioning without shock and therefore without risk of damaging the dissolver wheel during the installation of the of the new roller;
- a time saving on the maintenance operation (1 week saving on a total duration of 3 weeks);
- internal control of the technology (Orano Temis, with the support of the CEA) which allows a better reactivity in case of failure.

The economic benefit to the Orano La Hague reprocessing plant will be further examined in the next phase of the EGRRS work. For example:

- gain of XXX hours of plant availability;
- a reduction in the estimated maintenance cost of YYY%;
- a reduction in exposure of ZZZ%.

Figure B.33. Force feedback tele-operated maintenance of the rollers of the dissolving wheel

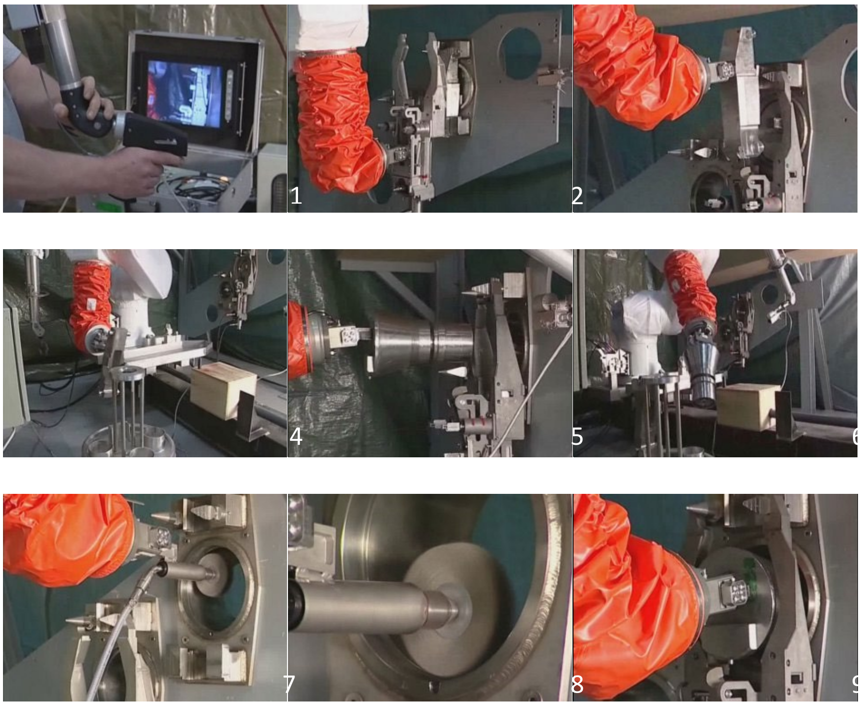


Figure B.34. Force feedback tele-operated cleaning operation of the inter-bucket space of the dissolving wheel

In order to keep up with the evolution of the Stäubli robot range (RX160 now replaced by the TX2-160), Orano Temis has continued developments to adapt the remotely operated robot solution with force feedback. Thus, their current product named TEΩ600 is based on the RX160 TAO:

- radiation resistance (integrated dose): 1 Mgy;
- load: 600N;
- rest of the system is identical to RX160 TAO (Haption^{TM} master arm, TAO2000 solution);
- fine force feedback with force sensor;
- force feedback by measuring the motor currents. This less expensive solution offers a slightly coarser force feedback, but allows in return to have it on all the axes, which makes it possible to manage contacts occurring at any point of the arm and not only at the end effector.

This TEΩ600 system will be used for dismantling operations with laser cutting and disc cutting processes at the UP2-400 plant being dismantled at La Hague (Figure B.35). The first 2 sites are scheduled for 2022 and others are already planned.

Figure B.35. The TEΩ600 system cutting of 2 dissolvers in the UP2-400/HADE Workshop; cutting equipment in a contaminated area with the TEΩ600 robot mounted on a mobile platform

DEROSA (semi-automatic robotic cutting)

Orano has also developed a specific system for dismantling operations in a moderately irradiating environment. This non-hardened system also uses the Stäubli RX160 manipulator robot and is designed to perform trajectories in unknown or evolving environments.

The DEROSA system includes:

- A standard RX160 robot and its rack. The robot is unchanged so its cost, maintenance and mean time between failures (MTBF) are known and controlled.

- A set of cameras and a 3-D scanning system embedded on the robot.

The developed function allows the operator to scan his environment, to realise in real-time a 3-D graphic reconstruction (cloud of points) of the chosen working area. He can also draw directly on this graph the trajectory of the robot, the system ensuring the management of the anti-collision with the environment thanks to the cameras.

Figure B.36. Scan of the working area (monitoring on the mobile monitoring and intervention [MMI] of the real position of the robot in the scene)

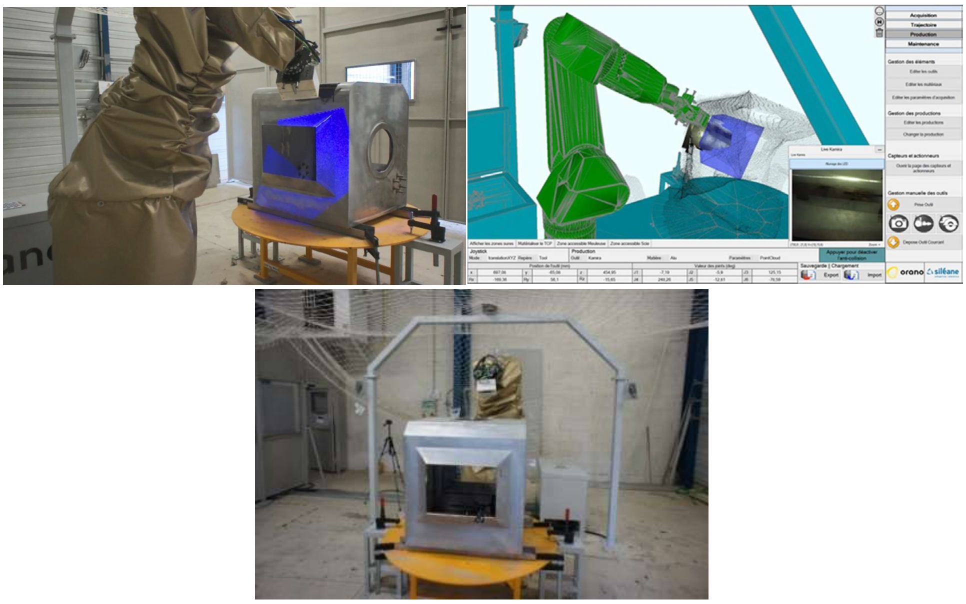
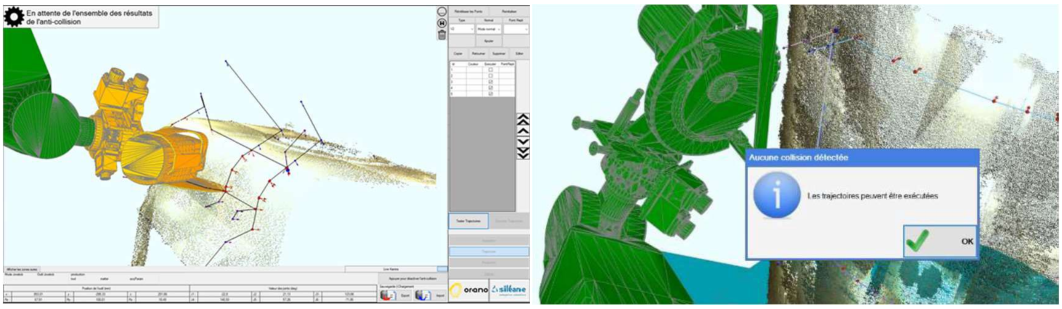


Figure B.37. (L) Definition of the trajectory in the point cloud; I Trajectory control and anti-collision


En attente de l'ensemble des résultats de l'anti-collision

Aucune collision détectée

Les trajectoires peuvent être exécutées

Figure B.38. Cutting operation

The system was tested under real but inactive conditions on a mock-up of a shuttle barrel from the Orano La Hague plant and on a mock-up of a CEA-type shielded enclosure. It was equipped with a circular saw, a grinder and a laser (simulated). Other tool couplings are planned.

Figure B.39. Shielded enclosure cutting test: 3 mm stainless steel with complex geometry

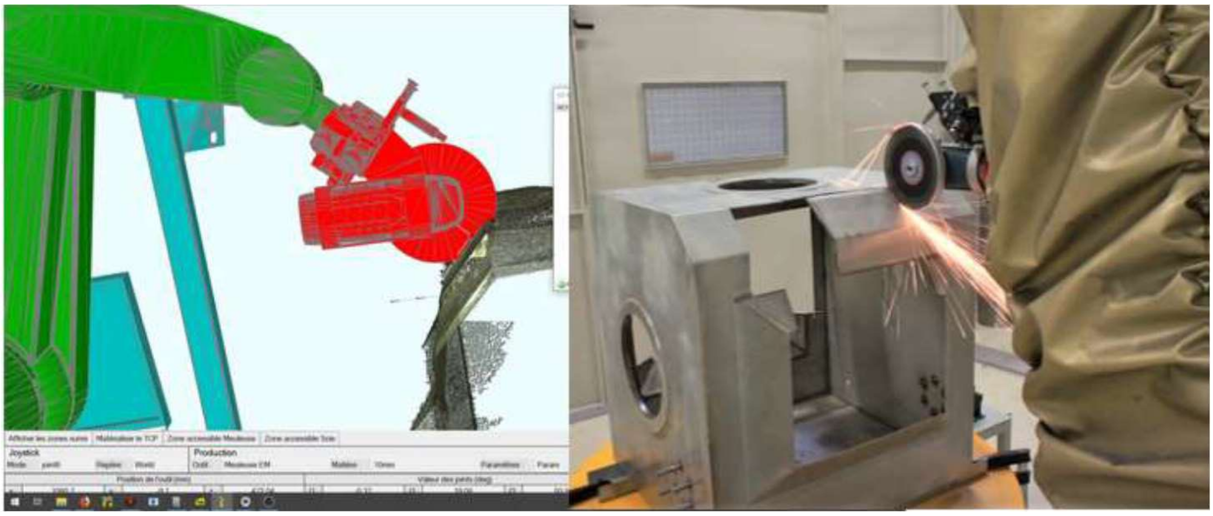


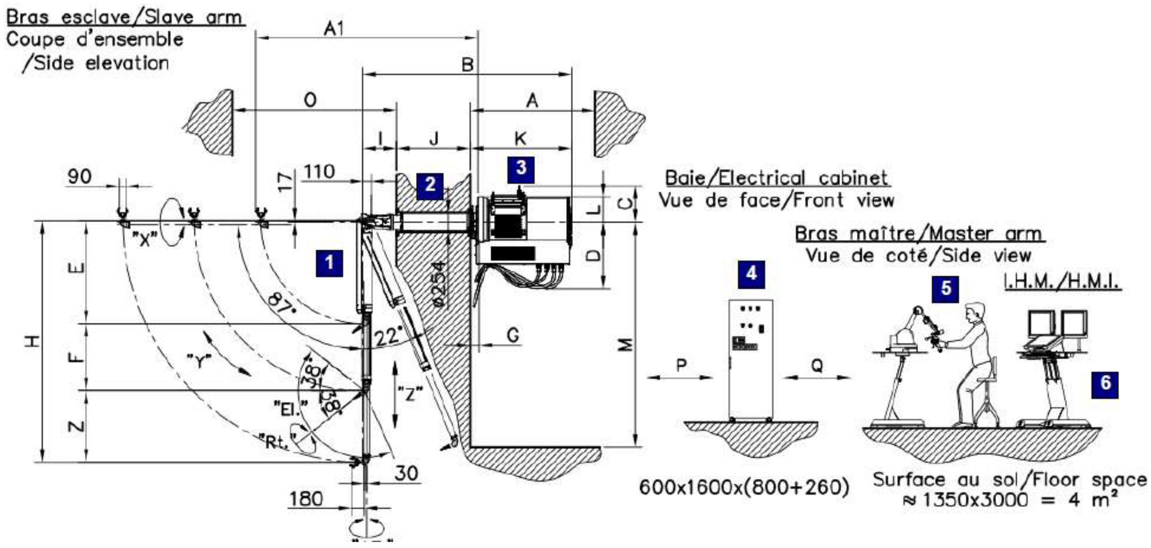
Figure B.40. Cutting of shuttle drums and endurance test of the robot - tool - consumable combination.

The advantage of the automatic mode for cutting operations is a better management of the trajectory, speed and effort than in the tele-operated manual mode. This reduces wear and tear on the consumables and avoids the need to stop work on the site.

MT200 TAO thru-wall telerobot (CEA-Orano)

The MT 200 TAO (Figure B.41) is a “thru-wall” force feedback telerobot whose special feature is that its telescopic slave arm and wall feedthrough are borrowed from the conventional MT200 mechanical telemanipulator (MSM) produced by Getinge - La Calhène. A MT200 is composed of three separate modules (slave arm, wall tube, master arm) and the actuator unit of the MT200 TAO takes the place of the master arm. A remote controller allows it to couple the slave actuator block to a force feedback master arm placed in the cold zone and chosen from the Haption™ range (MAT6D / Virtuose 6D).

Figure B.41. Architecture of the MT200 TAO telerobot



The control software provides precise balancing of the telerobot as well as the force feedback master-slave and thus exactly replaces the function of the MSM that it replaces. In addition, it offers the whole range of advanced assistance functions permitted by the generic TAO2000 software such as virtual mechanisms, virtual guides and the automatic robot mode. The development work for this system was carried out by the CEA on a specification from AREVA Hague (now Orano) as part of a multi-year collaborative programme.

The MT200 TAO was fully qualified from 2010 to 2011 by 10 months of tests in the vitrification cells of the Orano La Hague plant. Subsequently, its industrialisation has been achieved by Getinge La Calhène and 10 units were delivered to the plant and integrated into the production process of the plant.

Figure B.42. A typical workstation at the Orano La Hague reprocessing plant (left); the MT200 TAO telerobot in a ceiling work configuration in an Orano test cell (centre); a mixed workstation in a controlled area showing the MT200 TAO telerobot operated by the master arm MAT6D (HaptionTM) and a standard mechanical telemanipulator MT200 (right).

The MT200-TAO telerobot is now installed at the most heavily used workstations of the La Hague plant. The combination of the TAO control software and the actuator technology allows accurate and robust control of the system balance, the forces applied to the load and the mechanical transmissions, the position of the arm and the admissible speed limits defined by the operator. As a result, on the same highly solicited workstation (chiselling operation), the MTBF of the MT200-TAO remote robot is 500h against 50h for the slave arm of the MT200 mechanical remote manipulator. The reduction in the frequency of replacement, the concomitant reduction in operating stoppages and the reduction in the duration of operations results in a saving of several hundred euros.

In addition to the replacement of MT200 mechanical telemanipulators for the regular operation of the plant's processes, some MT200-TAO telerobots are also deployed on dismantling sites of shutdown installations. The photos below show the use of MT200-TAO telerobots on three workstations in the ELAN2B Workshop being dismantled at La Hague, in particular for cutting tasks. In each situation it is completed by a second mechanical telemanipulator MT200.

Figure B.43. Top, ELAN 2B dismantling workshop achieved using a combination of 3 telerobots paired with 3 mechanical telemanipulator MT200. Bottom, the results obtained in cutting tasks.

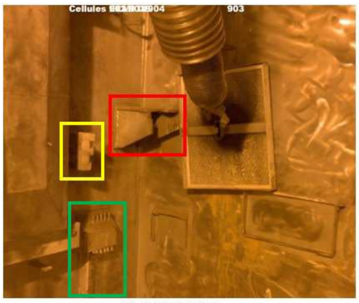


Photo avant coupe

Photo après coupe

For other dismantling applications, the MT200 TAO telerobot is also offered in synergistic combination with an RX TAO.

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B.9 Summary of robotics and automated systems in use in back-end applications

Manufacturer or Lead Organisation	**Applications**	**References**
A.N. Technologies Inc.	Nuclear operations; survey and measurement of hot cell at DOE site.	
AREVA	Laser cutting of piping by robot in France; Lower Girth Weld Inspection Tool (LGWIT) used at 2 US utilities.	
ASI Marine	Underwater ROV technology for visual inspection of structures at Canadian and US facilities.	
Blue Bear Systems Research	Unmanned aerial vehicle (UAV) technology for radiation detection and mapping in GPS-denied environments. Bluebear's RISER drone was previously deployed at Fukushima Daiichi. TRL 9	Blue Bear Systems Research Ltd (BBS–) - Products, "RISER", [Online], available: https://bbsr.co.uk/products/riser. Drone DJ, "UK RISER drone to map out radiation at Fukushima nuclear power plant", 2018, [Online], available: https://dronedj.com/2018/02/27/uk-riser-drone-to-map-out-radiation-at-fukushima/.
Boston Dynamics (now part of Hyundai)	BD (now Hyundai) manufactures biomimetic robots. Their first commercial product (Spot) is a four-legged mobile robot capable of navigating through stairs, walkways and other obstacles. Suitable for site characterisation, site surveillance and sample-return operations. Spot successfully performed radiological surveys at the Chernobyl site and is currently in use at 2 Canadian nuclear power plants. TRL 9	Ontario Power Generation (OPG), "New robot dog Spot turning heads at OPG", [Online], available: www.opg.com/stories/new-robot-dog-spot-turning-heads-at-opg/.
Bouygues Construction Solutions Nucléaires	Remote and robotic equipment used for nuclear dismantling and characterisation operations (Gobie, Murene, …)	
BROKK	Remote-operated equipment for dismantlement and segmentation operations and waste handling. Applied at US DOE sites, US commercial nuclear plants and UK decommissioning reactors.	
California Mechatronics Center	Wheeled robots for inspection of leaks in steam-affected areas and high levels of N-16.	
Carnegie Mellon University (CMU)	CMU's bioinspired snake-like robot (Unified Snake) is designed for navigation in uneven ground, slopes, channels, pipes and poles. Conducted visual inspections at Austria's Zwentendorf nuclear site.	Wright, C. et al, "Design and Architecture of the Unified Modular Snake Robot", 2012 IEEE International Conference on Robotics and Automation, Saint Paul, Minnesota, United States, May 2012.

Manufacturer or Lead Organisation	**Applications**	**References**
	TRL 8	New Atlas, "CMU's Snake Robot Explores Defunct Nuclear Power Plant", 2013, [Online], available: https://newatlas.com/cmu-snake-robot-explores-nuclear-power-plant/28235/.
CEA / Haption™	RX TAO, tele-operated maintenance robot at Orano La Hague.	Garrec, P. (2011), "Dedicated and industrial robotic arms used as force feedback telerobots at the AREVA-La Hague recycling plant", in *Proceedings of ANS EPRRSD – 13th Robotics and Remote Systems for Hazardous Environments • 11th Emergency Preparedness and Response*, 7-10 Aug. 2011, Knoxville, TN, United States.
Chiba Institute of Technology	Tracked robots at Fukushima.	
CRDI RTC	The Central Research Center of Robotics and Technical Cybernetics of the Russian Federation is a centre of competence in the field of research and creation of robotics, technical cybernetics and mechatronics. They have developed robots for non-destructive inspection of angular welded joints of reactor pipes as well as the cover of the PWR reactor unit (TRL?). In the field of emergency response of man-made emergencies UGV to perform work in areas with high radiation levels, localise gamma radiation sources in hazard areas was developed (TRL?).	Webpage with updated materials: https://rtc.ru/
Createc	Remote camera system for radiation imaging at UK sites and Fukushima.	
Curtis Dyna-Fog Limited	Application of wetting and contamination control agents used in US facilities.	
Cybernetix	Inspection/maintenance in French and Japanese facilities.	
D&S Fildem	Remote equipment used for nuclear characterisation operations (MIROS).	
ECA Robotics	Robotic solutions for a large range of purposes, include nuclear dismantling operations.	
Energid Technologies Corporation	Robot used for heat exchanger inspections in nuclear power plants.	

Manufacturer or Lead Organisation	**Applications**	**References**
ENGIE Solutions – Specialised Nuclear Services	Electrical master-slave (EMS) remote handling and (re)conditioning of nuclear waste.	Campaigns at ENGIE Electrabel Tihange Nuclear Power Plant (Belgium) and PreussenElektra Nuclear Power Plants (Germany). Lectured at ICOND 2016.
Flyability	Flyability's Elios collision-tolerant drone has been deployed at various nuclear power plants to investigate suspected leakages and conduct visual inspections in confined spaces. At Exelon PowerLabs, it was exposed to a cumulative dose of over 180 rem. In late-2020, a visual inspection of Chernobyl Reactor 5 was conducted successfully. TRL 9	FLYABILITY, "How Drones Can Help Nuclear Power Plants Reach ALARA Goals", [Online]; available: www.flyability.com/articles-and-media/drones-nuclear-power-alara. FLYABILITY, "Elios 2 Tested at the Chernobyl Nuclear Power Plant", [Online]; available: www.flyability.com/news/chernobyl-mission. WORLD NUCLEAR NEWS (2021), New drone for mapping radiation in nuclear plants, www.world-nuclear-news.org/Articles/New-drone-for-mapping-radiation-in-nuclear-plants.
Fortum / Jyväskylä University of Applied Sciences (JAMK).	An inspection and cleaning robot for steam generators at the Loviisa nuclear power plant.	
Framatome	Virtual Remote Robotics for Radiometric Sorting (VIRERO) remote waste handling.	
FriGeo	Collection of samples by freezing at UK site.	
G.E. Hitachi	Robot for movement of rubble at Fukushima; inspection of underground piping at US nuclear plants.	
H3D	Gamma imaging, identification of sources of radiation, discrete low-level contamination.	
Idaho National Laboratory (INL)	Remote and automated systems for scanning and characterisation of soil contamination at US DOE sites.	
IHI Southwest Technologies/ IHI Corporation	Underwater robot used for inspection of tanks at nuclear power plants.	
Institute for Safety Problems of Nuclear Power Plants	Robots for sampling and monitoring at Chernobyl.	

Manufacturer or Lead Organisation	**Applications**	**References**
International Climbing Machines	Use of crawler robot to remotely inspect tank walls at US DOE Hanford site.	
iRobot	Maintenance, material handling and radiation monitoring by robots at Duke Energy plants; material handling and inspections at Fukushima; Wolf Creek bioshield inspections.	
James Fisher Nuclear Ltd	Moduman 100 is a dexterous, radiation hardened, 2-3 metre reach arm with high payload capacity (100 kg) designed to support sorting and heavy lifting operations during decommissioning. Previously tested at facility in West Cumbria. TRL 8-9	James Fischer and Sons plc – Nuclear, "ModuMan 100 Manipulator Brochure", [Online], available: www.jfnl.co.uk/files/8414/3412/0187/James_Fisher_Moduman_100.pdf
KHG	Remote and robotic equipment used in German research and power reactors.	
Kinetrics	Robots for radiation measurements and removal of high activity debris at a Canadian nuclear plant.	
Karlsruhe Institute of Technology (KIT) - Institute of Technology and Management in Construction (TMB)	Robot systems for the (semi-)autonomous exploration, decontamination and clearance measurement of contaminated wall.	
Korea Atomic Energy Research Institute (KAERI)	KAERI developed spent fuel check vehicle (SCV), which can travel at 30/sec and can automatically analyse spent fuel. Its compact size, weighing and weight less than 11 kg, allows it to be carried on a plane. The SCV had been selected in the "IAEA Robotics Challenge 2017," held in Australia. TRL 5	[Online]. Available: www.youtube.com/watch?v=IAFL-Ug8nFY
Korea Atomic Energy Research Institute (KAERI)	Underwater mobile robot was developed for the inspection of reactor vessel weld, which is guided by a laser pointing device. The robotic system is so small and compact that the inspection time is reduced and its handling is convenient. TRL 5	Kim, J.-H., J.-C. Lee and Y.-R. Choi (2014), "LAROB: Laser-Guided Underwater Mobile Robot for Reactor Vessel Inspection", *IEEE/ASME Transactions on Mechatronics*, Vol. 19, No. 4, Aug. 2014, https://doi.org/10.1109/TMECH.2013.2276889. [Online]. Available: www.youtube.com/watch?v=3S9yXjXZBN4

Manufacturer or Lead Organisation	**Applications**	**References**
Kraft Telerobotics	Remote controlled robots used for nuclear dismantling operations (Kraft Predator).	
Kurion	Mechanical systems for monitoring, lifting and cutting operations at US DOE sites and Fukushima.	
LaCalhene	Fully electrically powered remote handling systems with software control for dismantling and decommissioning.	
Magics Instruments	Sensing and control platform maintenance and inspection Tools. Digital sensing and control of robotics, remote handling equipment and manipulators. Reduction of analogue cables and ease-up cable management. Post-accident sensing networks. Lifetime extension programmes.	
Magnox	Decontamination and volume reduction of highly contaminated skips; automated shaver decontamination installation and use.	
MDA Corporation	MDA developed the Light Duty Utility Arm (LDUA) for the US DOE, to inspect the underground storage tanks at Hanford, Idaho National Engineering Laboratory (INEL), and Oak Ridge National Laboratory (ORNL). TRL 9	Carteret, B.A., "Light Duty Utility Arm System Applications for Tank Waste Remediation", Westinghouse Hanford Company, October 1994
Mitsubishi Heavy Industries (MHI)	MHI's decontamination robot "MEISTer" was designed to perform vacuuming/blasting decontamination, concrete core sampling and collection of rubble in the reactor buildings at Fukushima. TRL 9.	Mitsubishi Heavy Industries (MHI), “MEISTER Remote Control Robot Completes Demonstration Testing at Fukushima Daiichi Nuclear Power Station – Performs Decontamination Work and Concrete Sampling”, 2014, [Online], available: www.mhi.com/news/story/1402201775.html.
New Millenium Nuclear Technologies International Inc.	System with automated components for the collection of concrete samples at US DOE.	
Nova Machine Products	Automated HydraNut tensioning and detensioning system used at US nuclear plant reactor vessels.	
NuVision Engineering	Hydraulic robotic arms and equipment, and waste material handling and decontamination at US DOE sites.	
OC Robotics	Snake arm robotic equipment for segmentation operations at Swedish and Canadian nuclear plants.	

Manufacturer or Lead Organisation	Applications	References
Ocean Modules	Ocean Modules develops underwater ROVs certified for use in nuclear environments such as the V8 M500N. TRL 9	Ocean Modules – References [Online], available: http://ocean-modules.com/references.html.
Orano	AZURo automated underwater cutting system for large components. TRL 9	www.orano.group/docs/default-source/default-document-library/conférence-virtuelle---espagne/2020-09-orano-waste-management.pdf?sfvrsn=e2c20bfb_8
Ortec	Automated measurement and assay systems for radioactive material and waste.	
Pacific Northwest National Laboratory and EIC Laboratories Inc.	Automated chemical analysis of tank contents at DOE.	
PaR Systems	Robotic equipment for radioactive material and waste handling at US DOE sites; main crane and mobile tool system for remote operations and clean-up at Chernobyl.	
QinetiQ	Robots for material handling and inspections at Fukushima.	
Rolls-Royce	Cleaning and inspection of small diameter piping.	
Savannah River Remediation, LLC	Various robots for tank cleaning at US DOE site (Savannah River Site).	
Shark Robotics	Unmanned ground vehicles that can be used in nuclear back-end activities.	
Siléane	Vision assisted robotic system used to sort, calibrate, handle, … (EDF is interested for waste management).	
UK Atomic Energy Authority, Ltd	Nuclear operations; development of remote handling equipment for ITER fusion reactor in France.	
Veolia	Veolia Nuclear Solutions has developed the Fukushima Inspection Manipulator and Fukushima Repair Manipulator (FIM and FRM) systems to locate and seal leakages and allow future removal of the damaged fuel and other debris from the unit 2 reactor. TRL 8-9	Veolia Nuclear Solutions, "Go Where No Human Can With Innovative Robotic Solutions" [Online], available: www.nuclearsolutions.veolia.com/en/our-expertise/case-studies/fukushima-daiichi-japan/go-where-no-human-can-innovative-robotic

Manufacturer or Lead Organisation	Applications	References
VideoRay	Mini-submarine ROV for monitoring and retrieval of samples from spent fuel pool at UK nuclear site.	
Zetec, Inc.	Robot crawler for inspection of steam generator tubes.	

Annex C: Detailed survey results on RRS barriers and impediments

Introduction:

What follows is a brief summary of the responses gathered for the industry survey on the use of robotics and automation in nuclear decommissioning with a total of 43 replies. It was disseminated among the EGRRS participants, their networks, members of the NEA Co-operative Programme for the Exchange of Scientific and Technical Information on Nuclear Installation Decommissioning Projects (CPD), as well as participants of the DigiDecom2021 (https://www.oecd-nea.org/EGRRS21). Given the relative small responses base and broad variety of responses, it was considered difficult to support definitive conclusions. No quantitative analysis on the data has therefore been performed. Nevertheless, some points of interest have been identified that might be useful when bringing to bear statistical tools onto the data if and when this is deemed suitable. The responses have also been viewed through the lens of the last couple of years of ethnographic fieldwork undertaken in the UK industry.

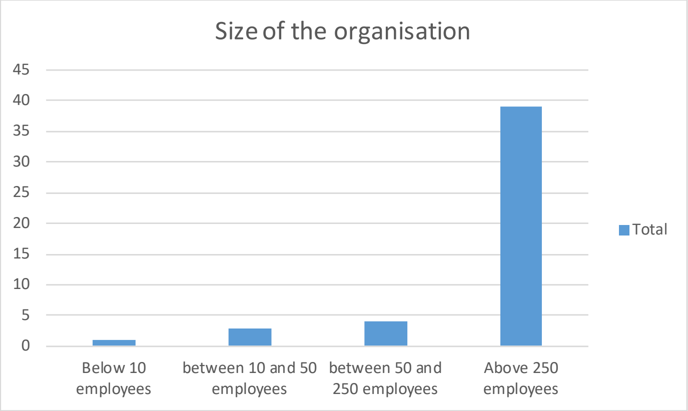
The initial approach was to examine the survey question by question and give some thought to the data collected, followed by a short summary of some of the issues that have been raised by the survey. Overall, the section where respondents were asked to rate the importance of the barriers from 1 to 5 yielded the most potentially relevant information. The section following this, which asks for written responses, is not as useful to interpret as the answers, where they were given, tend to speak to esoteric and context-dependent experiences depending on the nature of the work being carried out. Outside of these highly specific cases, this did not provide a great deal more information except for echoing some of the issues raised in the previous section.

Results and comments:

Below are the results to the questions and related comments, starting with three questions to broadly evaluate the participating stakeholders.

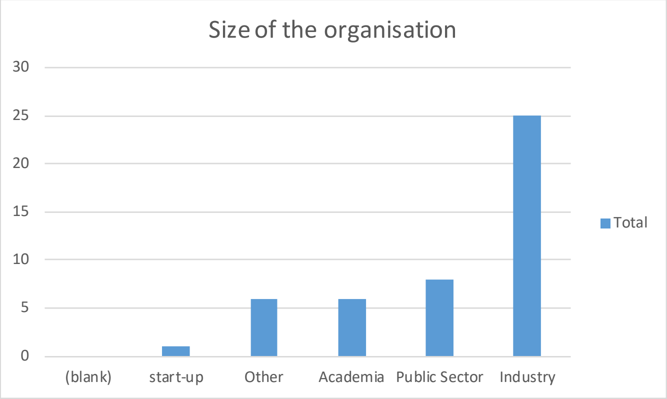
1. What size is your organisation?

Only 7 of the respondents had under 250 employees. So mostly the respondents were larger organisations, as shown in he following graph:



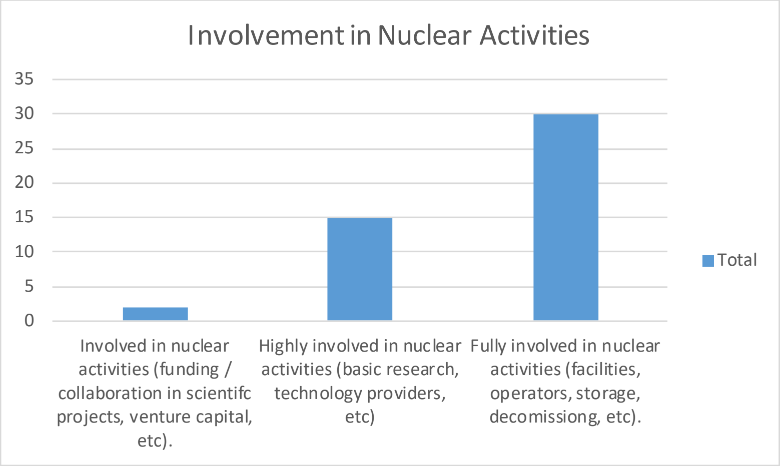
2. Which is the type of your organisation?

Mostly industry, with a few public sector and academic respondents:



3. (How) would you consider your organisation?

Either fully or highly involved in nuclear sector across the board:



4. Importance of impediments:

The following table provides comments on the responses to the proposed impediments identified by EGRRS. The refereced ranges in the assessement apply to the following scale:

1 – not important; 2 – somewhat important; 3 - important; 4 – very important; 5 – critical;

Impediments	Comment on the provided responses
E: Current manual techniques are adequate	A large spread found, 1-4. No obvious trend at a glance and didn't seem to coincide with the type of organisation. Perhaps some further statistical analysis might pick something with regards to some of the other attitudes.
F: Current use of robotics and remote systems is already at an appropriate level	Another wide spread of answers. Hard to establish a pattern with collected data set.
G: Lack of knowledge on currently available systems	Mostly in the 3-5 range. Very few seen in the range of 2. Overall it seems to be the case that there is perceived to be a belief that there is somewhat of a lack of knowledge regarding available systems.
H: Reluctance to adopt first-of-a-kind technology	This seems to be more strongly indicated to be an issue, although more data would need to be collected to confirm this, as there is a not-insignificant number of outliers.
I: Lack of robust system demonstration data	This was generally supported quite strongly in a similar manner to the previous question. With some exceptions, the answers also corresponded mostly with those from the previous question, which would be expected given their similar implications. A few of the answers strongly buck this trend, though.
J: Lack of broad international standards	Shows broad disagreement. Responses were very varied.
K: Lack of federal standards	As above, the results varied widely.
L: Lack of formal certification processes	Varied results, but there is some suggestion that research bodies don't believe this to be a significant impediment. This may be down to a lack of experience with formal certification, or it could be suggesting that the formal certification process itself may be considered an impediment, therefore the lack of it is not seen challenging. It depends on how the question is interpreted. Experience suggests the certification process can be challenging for those unfamiliar with it, but comparatively straightforward for those who are.

M: Lack of radiation hardness assurance for RRS	A broad range of results, although the results tended to fall more strongly on one side of the question or the other (responces on the extremes 1 and 5).
N: Difficulty achieving acceptance by safety authorities	Although there are not enough responses to make a clear statement in this regard, it is interesting that it was generally perceived to be a major hindrance except by the start-up and public sector respondents who it might be assumed have more experience with this type of approval. This could be a clearer indicator that there is a perceived difficulty more than an actual one. This is possibly one of the more interesting trends that might benefit from further analysis.
O: Concerns with equipment reliability	With a couple of exceptions this does seem to be a widespread concern. Probably one of the clearer trends.
P: Concerns with availability of spare parts	Very broad range of results, difficult to ascertain anything meaningful from the responses.
Q: Burdensome maintenance requirements	A broad range of responses, so it is equally difficult to draw any concerns over this. It seems likely that with this and the above question it is difficult to respond broadly to something which most likely is assessed on a case-by-case basis.
R: Lack of qualified operators	Again, a wide range of results with no clear pattern at this point.
S: Lack of qualified vendors	There is what appears to be an interesting pattern forming here, with industry being concerned with this while the research-based respondents were not. This is an aspect which has been observed in research being conducted in the United Kingdom, where those organisations supplying the technology believe themselves to be qualified while industry does not. This is often a case of potential suppliers not knowing what they do not know, through lack of experience dealing with the industry. This leads the nuclear industry to favour more experienced suppliers with whom they have dealt with over long periods and be sceptical of new developers entering the industry. This appears to be potentially borne out with the responses in this survey.
T: Burdensome training requirements	Broadly speaking, the responses seem to trend towards this being a low or medium concern for industry, while researchers did not consider this to be a major issue.

U: Systems are too complex to use	These seemed to follow the results of the previous question quite closely, which seems logical given that the complexity of the system is the primary concern of both.
V: Reluctance of workforce to use advanced systems	Very mixed responses from this question.
W: Work force concerns with job loss	Although there is some variation, this seems to trend quite low as a concern. There are plenty of "1" responses (not important) here, and no "5"s (critical) at all. This is also in line with the responses encountered over the course of research being conducted in the United Kingdom, where this is generally not considered to be a major issue despite it being raised as a potential factor, most likely due to the general discourse surrounding robotics and automation in the mainstream media. As an aside, research shows it was more often raised than greater efficiency of equipment leading to a drop in the amount of overtime available to workers, rather than complete job loss, and that this could generate some negativity towards these systems. Overall job security was rarely considered to be a problem, however.
X: Lack of a realistic cost-benefit model	With the exception of the start-up and R&D respondents (perhaps understandably) this seemed to be a general concern among most respondents.
Y: Capital investment is too high	With the exception of some outliers, this seems to be a moderate to major concern, which is in line with the responses based on the cost-benefit considerations.
Z: *Equipment life cycle costs are too high*	The mixture of responses here seems to be in line with other questions regarding the potential costs of the equipment.
AA: *Systems are too task-specific*	There was a fairly high variation in the responses, so it is difficult to ascertain much on the given data set.
AB: *Concerns with performance in an industrial environment (heat, humidity, dust etc.)*	Most responses seemed on the medium to lower end for this question.
AC: *Equipment cannot fully complete the task; some manual effort still required*	A very mixed series of responses with no clear pattern. Most likely this depends on the particular case as to whether this is a concern or not, and the factors which may be considered here (radiation exposure, cost etc.).
AD: *Concerns with damage to critical plant equipment*	Mixed responses for this question.

AE: *Difficulties routing required utilities (e.g. power and control cables)*	Responses varied from 1 to 5 across the board. No doubt this would be highly dependent on both the type of equipment, as well as influenced by prior experiences with new and existing technology.
AF: *Systems too large/heavy for restricted-access spaces*	A wide variety of responses again. Most likely because it is so dependent on the technology and the nature of the specific deployment as to whether this is a concern. Context is important here.
AG: *Lack of an accepted radiation exposure reduction cost benefit factor*	A wide variety of results here. This might vary based on the weighting to which each organisation places on radiation exposure and cost benefit, rather than anything to do with robotics and automation itself.
AH: *Potential for radioactive contamination of equipment/systems*	The results were quite mixed, making it difficult to guess at a trend at work. Interestingly some of the results seemed to skew towards the extremes of the scale with several 1s and 5s. Overall it seems to be a comparatively low concern in the context of this survey but for some respondents it becomes an absolutely key factor. A wide range of what appears to be individual difference seems to factor in here.
AI: *Concerns with performance in high radiation fields*	A fairly mixed series of results.
AJ: *Concerns with personnel safety*	A very mixed series of results, with the interesting exception that the public sector respondents all had very low concerns for this aspect.
AK: *Potential for high radiation exposure retrieving malfunctioning equipment*	This seems to be a moderate concern for most.
AL: *Potential for personal injury retrieving malfunctioning equipment*	The distribution of results seemed to be broadly in line with those for the previous question, perhaps averaging slightly lower.

5. Barriers and impediments

Based on the back-end related barriers and impediments, the comments reflected the following:

- *Low-level systems e.g. hand-operated tools for underwater operations.*

  The academic respondents seemed quite focused on the technical challenges, especially with aquatic systems. The industrial issues were spread across several of the categories mentioned in the previous questions, including safety, training, reliability and some mentions of a general cultural resistance to change or inertia. Several of the respondents did claim there were no specific barriers or that they were already using such technologies.

- *Automatically operated tools e.g. programmable torch cutting machines.*

  Where there were concerns these would often mention concerns on the dependability of software.

  Telerobotics, such as remote, mechanical/electrical master-slave manipulators (MSM/EMSM), and computer assisted master-slave systems with or without force feedback.

  Fewer responses for this question, several respondents saying this technology was already in use.

- *Programmable controller with interchangeable memory e.g. storehouse cranes.*

  Many of the responses here suggesting little or no experience with these technologies.

- *AI driven tools e.g. autonomous working robots.*

  The most common barrier here was clearly a lack of standards and difficulty creating safety cases.

- *Other classifications or specific robotic and remote systems (to be detailed further).*

  Various responses for this category that seemed heavily contextual based on the respondent's area of expertise and context.

General questions to complement the survey:

- *Based on the categories above, are there robotic and remote systems you would like to apply but were not able to? If yes, please elaborate on the kind of robotic and remote systems and the existing barriers and impediments towards its application.*

  The answers here were quite specific to the respondent, often echoing the range of barriers and impediments mentioned previously.

- *Could you please list applications or test of autonomous systems in the nuclear back-end? Please elaborate on the additional impediments in conjunction with such systems.*

  Not many responces received. This question might have been misunderstood or otherwise people felt incapable of responding.

Summary

It is obviously difficult to establish overall trends using a small set of results such as the above. Although a proper quantitative analysis may reveal some more patterns, whether this could be considered conclusive in any way uncertain. Nevertheless, the outcomes suggest topics for potential further investigation. In some categories there was a notable difference in opinion between the various types of organisations. More specifically, organisations that can be assumed to be providers of the technology (such as academic institutions) had a different perspective on impediments for adoption of robotics than organisations representing potential end users within the industry. This was clearly visible in the responses referring to the "lack of qualified vendors". Generally speaking, the developers of the technology believe that the vendors (potentially themselves) are qualified, whereas the industry has concerns in this regard. With such a small number of respondents so far, the survey alone does not necessarily identify an international pattern. Nevertheless, the pattern is notable and is in line with the personal experience of some the authors of this document.

There are various issues regarding the development of robotics when taking into account some of the particular challenges in nuclear decommissioning environments. Many of the researchers working with robotic solutions have very little first-hand experience and, hence, understanding of the sites where the technology will be deployed. There may be debris that can snag a tether, uneven surfaces which present challenges for locomotion, the visibility in underwater environments may be exceptionally poor, etc. These are aspects which those working in decommissioning are highly familiar with, but there is often very little communication between the developers and the potential users. Test deployments will often fail due to such unanticipated circumstances, reducing confidence of the end-user community in the technology for a long period. When it comes to further analysis, it could be productive to separate research organisations and industrial users in the analysis, as a misalignment in beliefs, experience and expectations could be an indicator of a barrier to adoption in itself.

Annex D: RRS cost benefit analysis methodology

FBFC International is a former fuel assembly manufacturing plant in Dessel, Belgium, which is finishing its decommissioning in 2021. Founded in the early 1960s, it produced uranium fuels slightly enriched (< 5% 235U) starting from uranium oxide powders until final assemblies ready for use in electricity-generating nuclear power plants. Uranium production was stopped in 2012 and the decision was then taken to dismantle and denuclearise the plant with the intention of an unrestricted site release.

Site survey

The objective was the "unconditional release of the site" which implies the absence of residual contamination in buildings but also the absence of soil pollution. Potential sources of soil pollution included leakage of underground effluent pipes, historical spills and possible uncontrolled pollution during dismantling operations.

Concerning the soil issue, the first step was a site survey based on the EURSSEM: the site was split up into areas of different risk categories based on their history before and during the production period but also during decommissioning operations. For each class, a different number of sample positions was required to reject the hypothesis that the area is contaminated. Exact number depended on the expected variation of measured activity concentration in such a class. This could be derived from a preliminary site survey: at FBFC International, results from a prior remediation project of more limited scope in 2001 were reused to this end.

It is worth pointing out that EURSSEM recommends an additional 100% screening of the ground for hotspots for class I, e.g. using a mobile gamma spectrometer. However, given the radionuclides used at FBFC International (234U, 235U and 238U only), the most significant gamma emission line being at 185.7keV (235U), this would result in a screening depth too thin to serve its purpose. Instead, it was opted to place additional sampling positions near all potential sources of hotspots: along piping pathways, around and under retention pits and along foundations. The repercussion was a large increase in the number of sampling positions.

Soil remediation

The volume to remediate was then minimally defined as the bounding volume defined by the first sample points below the clearance limit of 1Bq/g. Nevertheless, the volume excavated was often larger, taking into account practical concerns as grouping of small neighboring volumes, having an excavation slope < 45° to avoid the created pit from caving in (occupational safety) and use of industrial equipment (cranes, sand-pumping devices). Sample positions were marked out again after excavating operations to verify that all contamination has been removed and to map the excavated surface for record keeping. Excavated soil was buffered in different storage areas on site.

The second step in the strategy was to send the excavated soil through a dedicated system for radiological measurement and sorting designed by NTES and named FREMES. Soil was forced into a fixed geometry by conveyor belts and ran past two high-purity germanium spectrometers that picked up the 185.7keV line of 235U to determine the activity content. Together with a scale mounted on the same belt, the activity concentration of the soil could be determined per batch of ±120kg at speeds around 10 to 15 ton/hour. The batch of soil was then directed towards one of three possible output streams:

- < 1Bq/g: unconditional free release. In first instance, this sand was and will be used to refill the excavation on site.
- 1-10Bq/g: conditional release. With a dedicated license granted by the Belgian authority, this material was transferred in big bags to a conventional landfill for hazardous waste.

- ≥10Bq/g: transferred to the Belgian national radioactive waste management agency (ONDRAF/NIRAS).

Results

Overall, 38 000 tonnes of soil were excavated and sent through the sorting equipment FREMES from January 2018 until December 2020, which was the end of FREMES operation:

- 36 000 tonnes soil unconditionally released
- ~2 000 tonnes soil sent in a depository for hazardous waste
- ~1.3 tonnes sent to ONDRAF/NIRAS as radioactive waste (> 10 Bq/g)

The example case described in this Annex compares FREMES and ISOCS. FREMES is a belt conveyor free release measurement system for radiological characterisation of concrete and construction waste. ISOCS means In Situ Object Counting System. The site has 38 000 tonne of soil that is to be observed for radiation. There are three scenarios: remediation with the Canberra ISOCS system, remediation with the FREMES system, and remediation with ISOCS systems with the same capacity as FREMES. The last two options are comparable as the same volumes of soil are in focus. It is relevant to make a comparison in respect to the main drivers: operation scheme, CAPEX, OPEX, risks, staff, time of execution, licensing and regulatory process, social acceptability, and knowledge management.

<u>OPERATION SCHEME.</u> Usage of robotic or digital solutions may lead to significant changes in the execution approach in comparison with the same task executed by staff. In some cases with high radiation, it may substantially decrease expenses on radiation safety. Moreover, it is important in difficult-to-reach areas.

Influence:

- *Robotic and digital solutions may use the same operation scheme as a non-robotics approach or be executed in a different way.* In medium and high radiation zones, a non-robotic approach needs special infrastructure to protect staff during operation while for robotics these solutions are not necessary and only require contingencies for intervention and retrieval in case of failure. This fact alters the operation scheme, first requiring huge investments but turning profitable later. Moreover, such an operation scheme provides more safety.
- *Robotic and digital solutions may be more suitable for the execution of specific tasks.* In some cases, there are specific conditions (hard-to-reach places) where there are significant operational scheme differences between robotic and non-robotic approach, such as objects that are difficult to access or very dangerous for humans.
- Special equipment may be necessary for service and repairing.

Case/Example:

The operation scheme differs in the number of pieces of equipment: 1 for FREMES versus 20 for ISOCS. This difference results in various distinctions for other drivers. So the FREMES technology is 20 times more effective than 1 ISOCS, according to this assessment approach.

CAPITAL EXPENDITURES (CAPEX). In some cases, use of special robotic and digital solutions will result in additional CAPEX in comparison to non-robotic approaches with standard equipment. As a result, capital expenditures on direct task-related equipment with robotics execution is usually higher than with non-robotics. However, the robotic system cost cannot be examined in isolation. The overall CAPEX on a project can be lower with robotic solutions due to the possibility of simplifying, eliminating or reducing other equipment or building space associated with the project.

Case/Example:

CAPEX of 1 FREMES is EUR 10 000 000. CAPEX for 1 ISOCS is EUR 700 000, so for 20 ISOCS it is EUR 14 000 000, much higher than for FREMES. The life cycle of FREMES is 10 years longer than that of ISOCS (16 vs 6), so the efficiency of the former technology is evident.

OPERATIONAL EXPENDITURES (OPEX). Robotic equipment will often reduce the OPEX required to complete a task or project by reducing or eliminating manual labour, as well as the associated personal protective equipment (PPE) for the staff. Robotic approaches may also save on schedule time due to higher productivity and reduced task times. However, additional costs associated with equipment maintenance also need to be considered.

Case/Example:

The different numbers of units define the number of necessary personnel. One FREMES needs four workers, with an annual cost per staff of EUR 400 000. Twenty ISOCS are likely to have more personnel: 120 people and annual cost of EUR 12 000 000. The huge gap is between these figures. Costs of site maintenance are equal.

RISKS. Robotic and digital solutions may severely influence both the probability and impact of risks.

Influence:

- *No risks devoted to human factor (decrease of risks number).* Personnel can work outside the dangerous zone and avoid handling radiated objects.
- *Changes in probability and impact of risks for staff and civilians due to incident and accident.* With good software and hardware, the human factor is eliminated and operations are more accurate.
- *Cost of insurance (decrease of expensive staff insurance).* Fewer workers need fewer insurance certificates and the cost also decreases as the work becomes safer.
- *Changes in expenses on risks mitigation.* Safer technology provides lower risk for personnel, resulting in less money spent on risk mitigation.

Risk is defined as the probability of the risk multiplied by its impact:

$$Risk = Probability * Impact$$

Weighted Risk means risk multiplied by mitigation expenses:

$$Weighted\ Risk = Risk * Expenses_{Mitigation} = Probability * Impact * Expenses_{Mitigation}$$

Case/Example:

The FREMES has higher operational risk as only the one unit is in operation. However, the technology has proven its reliability. The 20 units of ISOCS have lower operational risk as they are diversified. Nevertheless, FREMES decreases risk for personnel, which means lower expenses in this sphere.

STAFF. This driver may be a part of OPEX as the cost per working hour in the project. However, robotic and digital solutions may also have more indirect consequences such as a global decrease in staff for certain applications in other projects, expenditures on certification and education, pension and other aspects which are different not only from case to case, but also from country to country.

Influence:

- Expenses for education, qualification and certification. New technology needs higher initial expenses especially for personnel education, qualification and certification. However, such costs are recompensed, as the innovations tend to improve efficiency.
- Extra payment for risk and work in dangerous conditions. As it was mentioned, the lower risk decreases such expenses, making the project more profitable.
- Extra pension payment.
- Insurance. Innovations result in lower number of workers so this decreases the insurance cost.

Case/Example:

The FREMES technology has significantly fewer staff and not only lower cost for wages but also lower training costs. The technology increases the safety of personnel.

TIME OF EXECUTION. Even assuming other drivers are the same for robotic and non-robotic solutions, the faster decommissioning work is finished the earlier the area can be rehabilitated and used for other purposes.

Influence:

- Earlier refund of reserves for decommissioning liabilities. New technology shortens the time of execution, which creates more opportunities for other purposes.
- Earlier completion of decommissioning and rehabilitation provides opportunities for commercial reuse of a brownfield or greenfield decommissioning investment.
- Decrease of total maintenance expenses.

Case/Example:

As the case equalises the annual observed soil volumes, the time of execution is the same, about two years. This is a good indicator for such volume of work.

LICENSING AND REGULATORY PROCESS. Previous approval by the regulator of a project's robotics solutions may lead to easier and faster acceptance for another. However, licensing and supervision of the implementation of new (first-of-a-kind) robotics solutions may be more complex and take more time and money.

Influence:

- Easier process of licensing and regulatory supervision (for solutions with references such as ISOCS, however, 20 units need more time and expenses).
- Less cost and time on licensing and regulatory supervision (for solutions with references).
- Licensing and getting approval process for implementation of robotic and digital solutions depends on local requirements and the flexibility of the national regulator. Tests and trials are needed.
- International and regional certification may have a positive impact on the deployment of robotic and digital solutions in different countries.

Case/Example:

The ISOCS technology has a standard licensing procedure and known expenses. FREMES needs approval by regulators. This needs trials and tests to estimate the corresponding costs.

SOCIAL ACCEPTABILITY. Using robotic or digital solutions may seem more reliable and safer for local communities from a technical point of view and can help to gain social acceptance more quickly.

Influence:

- Robotics and digital solutions may be favoured by local communities as more technological, reliable and unbiased. Delegation of dangerous work and hazards to robotics and digital solutions decreases risks for humans and increases safety.
- Robotics and digital solutions may be viewed critically by local communities because of a potential decrease in employment.

Case/Example:

Social acceptability requires objective information as the topic is crucial for local communities. The volume of soil is huge and dangerous, so there is a need for reliable technology that can complete the task in a proper and safe way. Society expects the technology to mitigate risks and hazards and become more reliable than a human.

KNOWLEDGE MANAGEMENT. Decommissioning is a complex process and each project has unique issues that may lead to new know-how and innovative solutions. The deployment of robotic and digital solutions provides a range of opportunities for more effective accumulation and use of knowledge in decommissioning projects. This is particularly true for AI solutions, which can implement know-how in new projects faster than staff ganing knowledge and skills. An important issue is to save practical knowledge and skills for a long time – after the peak in decommissioning work in 2040-50 due to solving legacy issues, the number of decommissioning projects will be decreasing. The transition of knowledge and skills to new generations is important for safe and sustainable nuclear development.

Influence:

- *Accumulation of knowledge and know-how for higher efficiency of decommissioning.* R&D projects and new knowledge lead to innovations, which make the processes more efficient and safer.
- Better opportunities for fast and widespread deployment of best practices and skills.
- *Storage and transfer of knowledge and skills through generations.* Robotics and digital solutions provide a range of opportunities to record best practices as well as knowledge about long-term dangers and hazards (disposals, etc.) for future generations. The software stores the best practices and AI improves skills for a safer and more precise performance. Technology accumulates data during operation and constantly develops.

Case/Example:

ISOCS needs a team to operate and the personnel should retrain and get certifications. ISOCS does not collect data. At the same time, FREMES is a technology that collects data without human intervention. Artificial intelligence studies data during operations, which decreases costs and uncertainty.

Detailed calculations for cost benefit analysis case study

PROJECT PARAMETERS	UNITS	VALUE
Volume of Soil	t	38000
Expected project length	years	3
Expected annual throughput	t/year	12666.67
Working weeks	weeks	48
Days per week	days	5
Working hours per day	hours	8
Total working hours per year	hours	1920

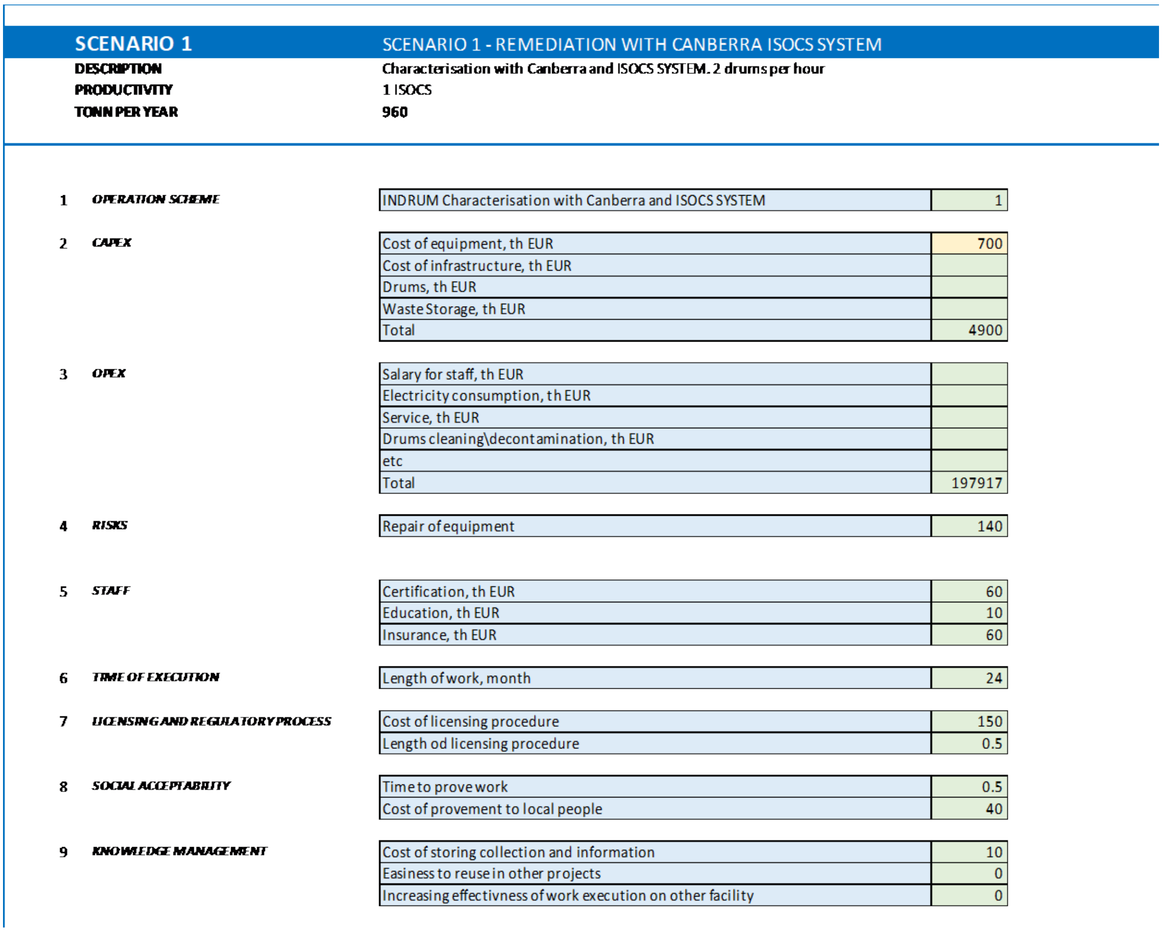
ISOCS PARAMETERS	UNITS	VALUE
Capacity of an equipment per hour	t/hour	0.5
Capacity of an equipment per year	t/year	960
Staff per equipment	person	6
Annual costs of 1 staff	€ th/person	100
Annaul costs for all staff	€ th	600
Cost of equipment	€ th	700
Life cycle of equipment	years	6
Service peroid	years	2
Service costs	€ th	50
Costs for lifecycle	€ th	150
Electicity power	kW/hour	2
Electricity consumption per year	kW/year	3840

FREMES PARAMETERS	UNITS	VALUE
Capacity of an equipment per hour	t/hour	10
Capacity of an equipment per year	t/year	19200
Staff per equipment		4
Annual costs of 1 staff	€ th/person	100
Annaul costs for all staff	€ th	400
Cost of equipment	€ th	10000
Life cycle of equipment	years	16
Small Service peroid	years	2
Small services	times per lifecycle	8
Small Service costs	€ th	50
Costs of Small Service per lifecycle	€ th	400
Capital Sevice Period	times per lifecycle	10
Capital Service Costs	€ th	500
Capital services	times per lifecycle	1
Costs of Capital Service per lifecycle	€ th	500
Total service cost per lifecycle	€ th	900
Electicity power	kW/hour	5
Electricity consumption per year	kW/year	9600

SITE PARAMETERS	UNITS	VALUE
Cost of 1 kW electricity	€ th	1
Cost of site maintenance(admin, security and etc.)	€ th/year	5000

	€ th	€ th	€ th
20	ISOCS	FREMES	ISOCS
Risk	20%	10%	20%
Repair of equipment (% of equipment cost)	2800	1000	140
Staff			
Certification, th EUR	1200	40	60
Education, th EUR	200	20	10
Insurance, th EUR	1200	40	60
Time of execution (years)	2	2	2
Licensing and regulatory project			
Cost of licensing procedure	3000	1590	150
Length of licensing procedure (years)	0.5	0.5	0.5
Social acceptability			
Time to prove work (years)	0.5	0.5	0.5
Cost of provement to local people	40	5	2
Knowledge management			
Cost of storing collection and information	200	2	10
Easiness to reuse in other projects			
Increasing effectivness of work execution on other facility			

GENERAL FACILITY AND DESCRIPTION	FBFC International is a former fuel assembly manufacturing plant in Dessel, Belgium which is finishing its decommissioning in 2021. Founded in the early 1960s, it produced uranium fuels slightly enriched (< 5% 235U) starting from uranium oxide powders until final assemblies ready for use in electricity-generating NPPs. Uranium production was stopped in 2012 and the decision was then taken to dismantle and denuclearize the plant with the intention of an unrestricted site release.
SITE SURVEY	The objective was the "unconditional release of the site" which implies the absence of residual contamination in buildings but also the absence of soil pollution. Potential sources of soil pollution included leakage of underground effluent pipes, historical spills and possible uncontrolled pollution during dismantling operations. Concerning the soil issue the first step was a site survey based on the EURSSEM: the site was split up into areas of different risk categories based on their history before and during the production period but also during decommissioning operations. For each class, a different number of sample positions was required to reject the hypothesis that the area is contaminated. Exact number depended on the expected variation of measured activity concentration in such a class. This could be derived from a preliminary site survey: at FBFC International, results from a prior remediation project of more limited scope in 2001 were reused to this end. It is worth pointing out that EURSSEM recommends an additional 100% screening of the ground for hotspots for class I, e.g. using a mobile gamma spectrometer. However, given the radionuclides used at FBFC International (234U, 235U and 238U only), the most significant gamma emission line being at 185.7keV (235U): this would result in a screening depth too thin to serve its purpose. Instead, it was opted to place additional sampling positions near all potential sources of hotspots: along piping pathways, around and under retention pits and along foundations. The repercussion was a large increase in the number of sampling positions.
VOLUME OF SOIL **potentially contaminated, t**	**38000**



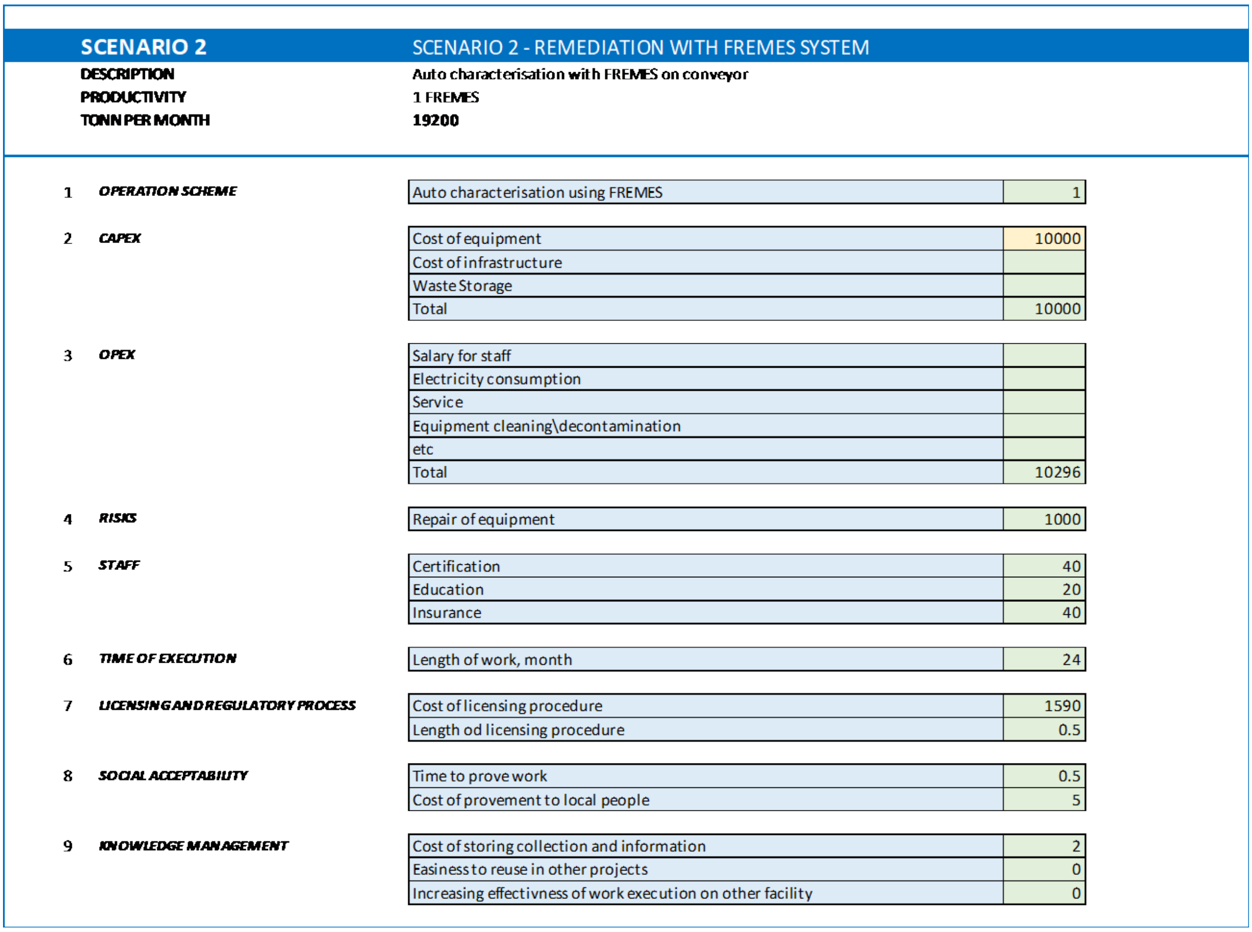
SCENARIO 1 SCENARIO 1 - REMEDIATION WITH CANBERRA ISOCS SYSTEM

DESCRIPTION Characterisation with Canberra and ISOCS SYSTEM. 2 drums per hour

PRODUCTIVITY 1 ISOCS

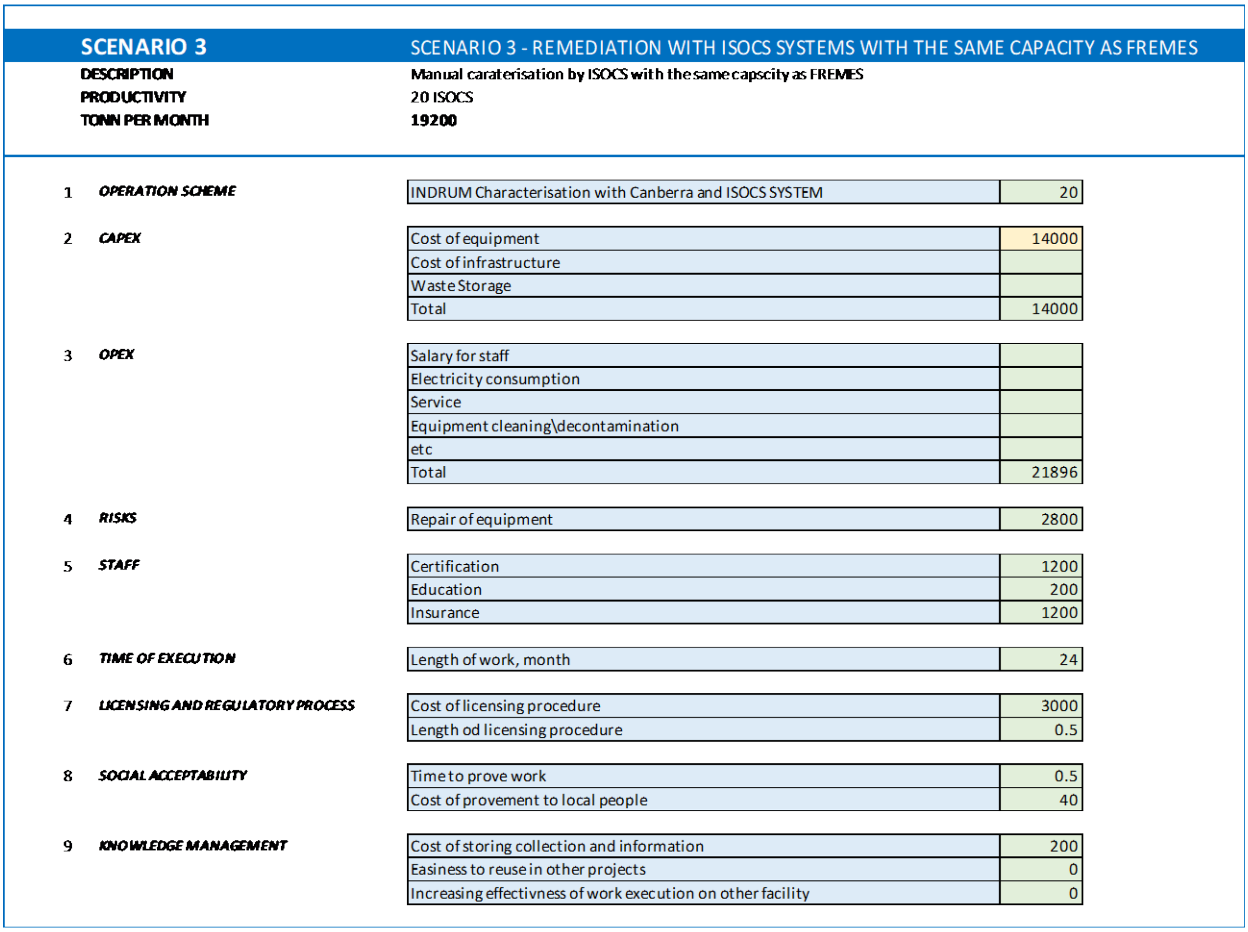
TONN PER YEAR 960

1	***OPERATION SCHEME***	INDRUM Characterisation with Canberra and ISOCS SYSTEM	1
2	***CAPEX***	Cost of equipment, th EUR	700
		Cost of infrastructure, th EUR	
		Drums, th EUR	
		Waste Storage, th EUR	
		Total	4900
3	***OPEX***	Salary for staff, th EUR	
		Electricity consumption, th EUR	
		Service, th EUR	
		Drums cleaning\decontamination, th EUR	
		etc	
		Total	197917
4	***RISKS***	Repair of equipment	140
5	***STAFF***	Certification, th EUR	60
		Education, th EUR	10
		Insurance, th EUR	60
6	***TIME OF EXECUTION***	Length of work, month	24
7	***LICENSING AND REGULATORY PROCESS***	Cost of licensing procedure	150
		Length od licensing procedure	0.5
8	***SOCIAL ACCEPTABILITY***	Time to prove work	0.5
		Cost of provement to local people	40
9	***KNOWLEDGE MANAGEMENT***	Cost of storing collection and information	10
		Easiness to reuse in other projects	0
		Increasing effectivness of work execution on other facility	0



SCENARIO 2	SCENARIO 2 - REMEDIATION WITH FREMES SYSTEM
DESCRIPTION	**Auto characterisation with FREMES on conveyor**
PRODUCTIVITY	**1 FREMES**
TONN PER MONTH	**19200**

1	***OPERATION SCHEME***	Auto characterisation using FREMES	1
2	***CAPEX***	Cost of equipment	10000
		Cost of infrastructure	
		Waste Storage	
		Total	10000
3	***OPEX***	Salary for staff	
		Electricity consumption	
		Service	
		Equipment cleaning\decontamination	
		etc	
		Total	10296
4	***RISKS***	Repair of equipment	1000
5	***STAFF***	Certification	40
		Education	20
		Insurance	40
6	***TIME OF EXECUTION***	Length of work, month	24
7	***LICENSING AND REGULATORY PROCESS***	Cost of licensing procedure	1590
		Length od licensing procedure	0.5
8	***SOCIAL ACCEPTABILITY***	Time to prove work	0.5
		Cost of provement to local people	5
9	***KNOWLEDGE MANAGEMENT***	Cost of storing collection and information	2
		Easiness to reuse in other projects	0
		Increasing effectivness of work execution on other facility	0



SCENARIO 3 SCENARIO 3 - REMEDIATION WITH ISOCS SYSTEMS WITH THE SAME CAPACITY AS FREMES

DESCRIPTION	Manual caraterisation by ISOCS with the same capscity as FREMES
PRODUCTIVITY	20 ISOCS
TONN PER MONTH	**19200**

1	***OPERATION SCHEME***	INDRUM Characterisation with Canberra and ISOCS SYSTEM	20
2	***CAPEX***	Cost of equipment	14000
		Cost of infrastructure	
		Waste Storage	
		Total	14000
3	***OPEX***	Salary for staff	
		Electricity consumption	
		Service	
		Equipment cleaning\decontamination	
		etc	
		Total	21896
4	***RISKS***	Repair of equipment	2800
5	***STAFF***	Certification	1200
		Education	200
		Insurance	1200
6	***TIME OF EXECUTION***	Length of work, month	24
7	***LICENSING AND REGULATORY PROCESS***	Cost of licensing procedure	3000
		Length od licensing procedure	0.5
8	***SOCIAL ACCEPTABILITY***	Time to prove work	0.5
		Cost of provement to local people	40
9	***KNOWLEDGE MANAGEMENT***	Cost of storing collection and information	200
		Easiness to reuse in other projects	0
		Increasing effectivness of work execution on other facility	0

Annex E: Case studies

E.1 Japan: Use of robotics in accident situations

In the case of the accident that occurred at the Three Mile Island Nuclear Power Plant (TMI) , one of the factors that contributed to the escalation of the accident was that the operators could not confirm whether the safety valves in the containment vessel were working. In response to this, a group of Japanese companies started to develop a system to support information gathering activities in the containment vessel, which is normally inaccessible to workers.

In Japan, it is required to improve the operation rate of the nuclear power plants. Another purpose of this system is to detect abnormal events in equipment and piping at an early stage and to respond to them as soon as possible. Therefore, research and development has begun to use robots for inspection, monitoring and operation inside the containment vessel.

The research and development of the robot was divided among three companies (Yamamoto, 1992).

(1) Floor travelling inspection vehicle: Toshiba

(2) Spatial travelling inspection vehicle: Hitachi

(3) Mobile manipulator for operation: Mitsubishi Heavy Industries, Ltd.

Assuming that the inspection will be conducted inside the containment vessel, the environmental conditions were commonly set:

(1) Temperature conditions: Maximum 70°C

(2) Humidity conditions: Maximum 100%

(3) Cumulative radiation dose: Cumulative 10^6R

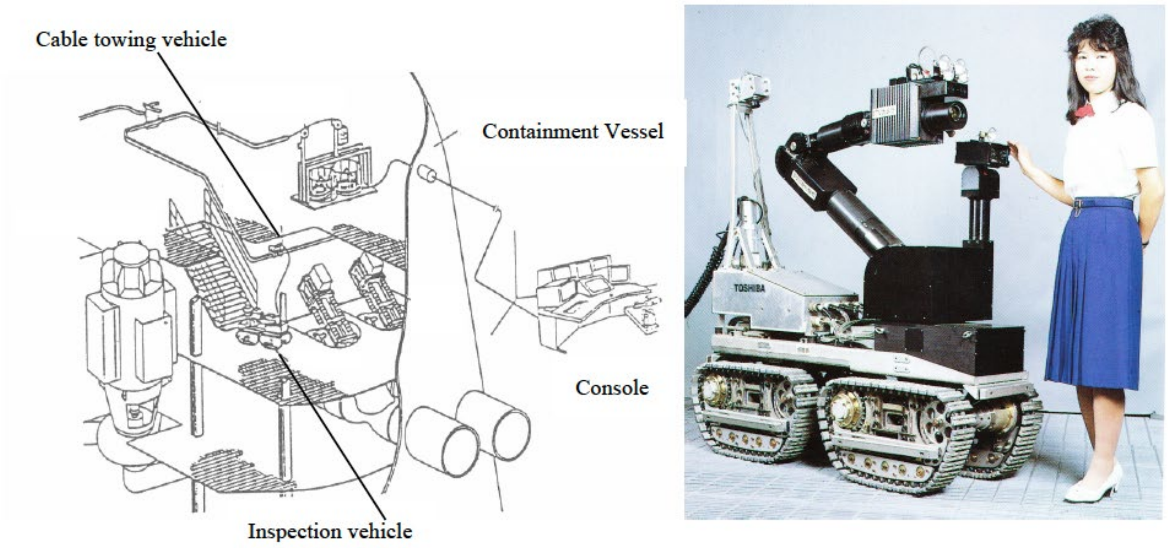
Since the interval between periodic inspections at a nuclear power plant was approximately one year, it was assumed that the parts replacement interval of the robot would be one year.

In 1980, there was no robotics research and development based on the constraints specific to these nuclear power plants, and it can be said that a wide range of research and development was challenged, from the components (machinery, electrical and electronic parts, etc.) to the robot system (Yamamoto, 1992).

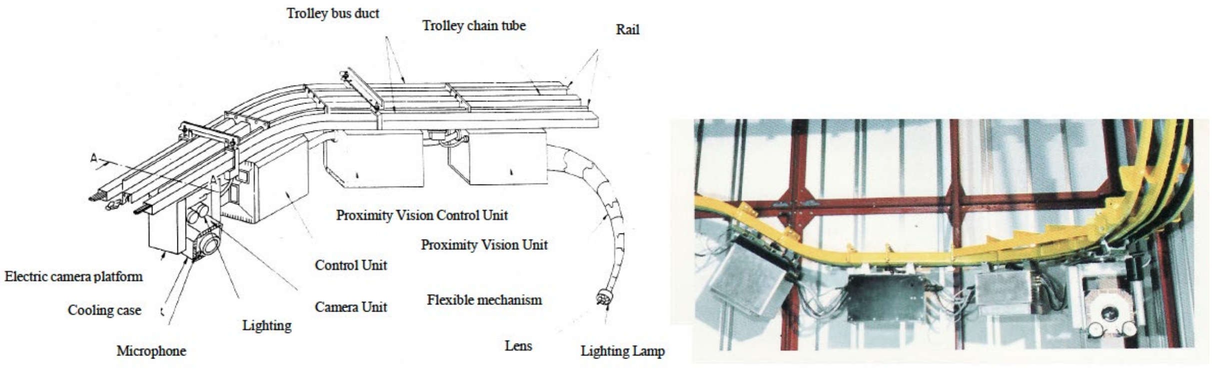
These three robots were developed by taking into account the constraints for each usage situation. Each robot is required to satisfy the above environmental conditions in its component parts as well as in the robot system as a whole. Various tests are conducted to confirm the performance and safety of the robots .

Figure E.1.1 shows the appearance of the three robots as a conceptual diagram of the containment inspection system. These robots are not stand-alone units, but are configured as a system to move and perform tasks (inspection, monitoring, and light work), which is highly evaluated. In addition, some of these robots and other robots that were researched and developed by electric power companies in co-operation with heavy electric power manufacturers were put to practical use in nuclear power plants or were subjected to demonstration tests, proving that robots are useful for inspection and monitoring. However, due to legal issues such as safety standards when adding robots to already completed power plants, economic issues such as the cost of robots and their maintenance, and technical issues such as robot operation, maintenance and preservation, power companies have been very reluctant to actively accept the robots.

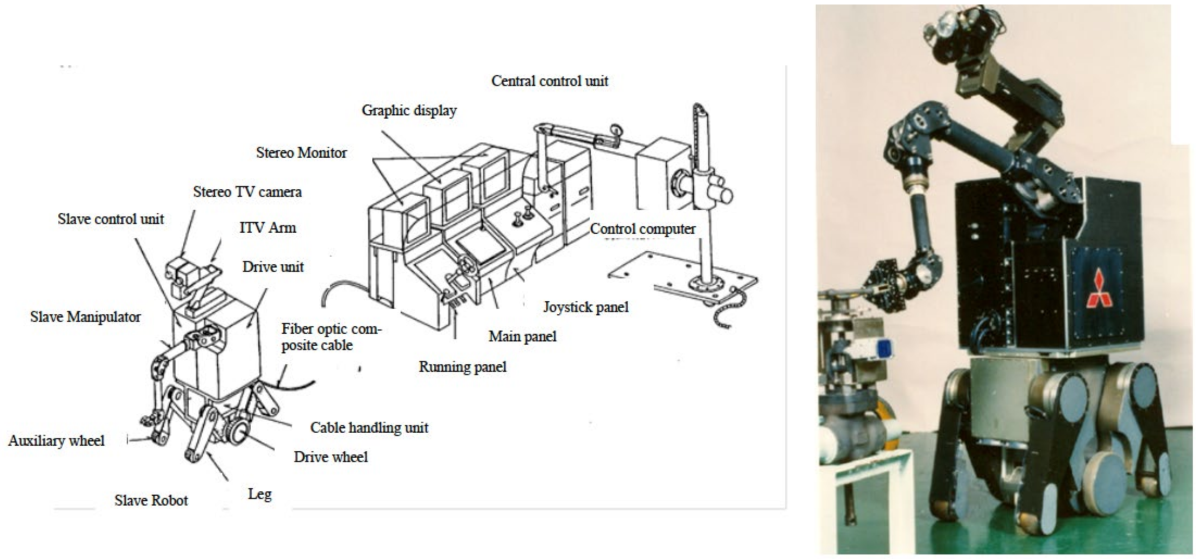
Figure E.1.1. Nuclear power generation support system: containment vessel internal inspection system



(a) Floor travelling inspection vehicle



(b) Room space travelling inspection vehicle



(c) Mobile manipulator

E.1.1 Robots for nuclear extreme conditions

(1) Outline

(a) Development history

The Robot Project was a national project that took place from 1983 to 1990 whose goal was to gather the most advanced robotics technologies and to research and develop systems that could perform tasks in extreme environments, those that are difficult for humans to enter.

The research and development of a robot for nuclear power plants was one of these tasks. The expected tasks were selected from among the various tasks in nuclear power plants that could only be performed by robots and that had clear advantages for robotisation. The tasks were those that could be performed with a high degree of reliability in a confined space and in a radiation environment, or those that could be made more efficient by the use of robots. Specifically, inspection, monitoring, and repair work (replacement of valves, piping, tanks, heat exchangers, and filters) in the containment vessel during operation and in areas with high radiation levels, and floor decontamination were discussed.

(b) Basic functions and system concept

It was expected that the robot would be able to perform more advanced work than dedicated machines, perform more efficient work, improve the operation rate, and perform general-purpose work that cannot be performed by dedicated machines by equipping it with intellectual functions as a so-called robot. The main basic functions of the robot are shown below.

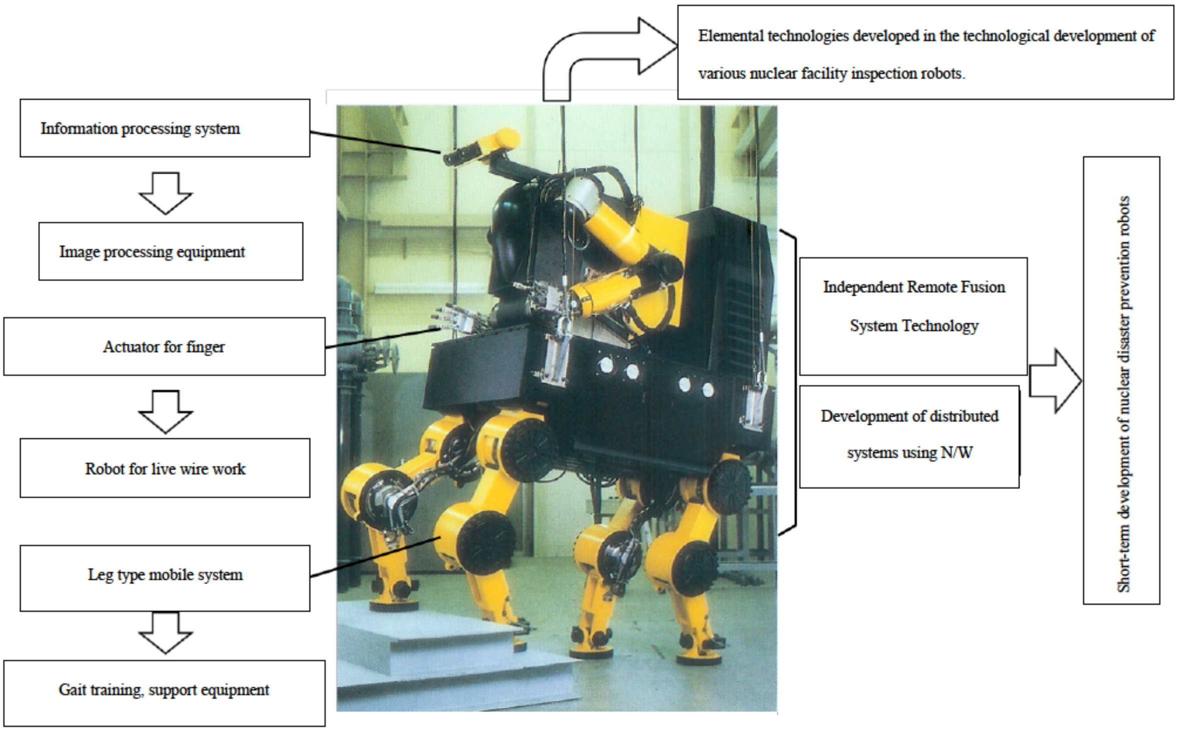
1. Autonomous remote control system is adopted because there are many irregular-shaped tasks.
2. Environmental conditions: 70°C, 100% humidity, radiation dose rate of 150 R/hr (approximately 1.5 Sv/hr).
3. Size, floor movement, obstacle crossing, manipulator function, perception function, information transmission function, remote control, reliability, maintainability.

(2) Lessons learnt and recommendations

Although the demonstration machine itself was not introduced to the field, Figure E.1.2 shows some of the elemental technologies that were developed during the construction process and are considered to have been put to practical use in industry.

In particular, the autonomous remote system technology is thought to have been used as the basic technology for subsequent robot systems of the same type, such as the disaster prevention robots developed in response to the JCO accident.

Figure E.1.2. Examples of practical technologies developed from the demonstration unit



E.1.2 JCO accident and nuclear accident response robots

(1) Overview

(a) Background of development

In September 1999, a criticality accident occurred at a uranium processing facility in Tokai Village, Ibaraki Prefecture. At this facility, there was no equipment to protect people from high radiation.

In response to this, the Ministry of Economy, Trade and Industry (METI) allocated a budget of approximately 3 billion yen to prepare the necessary equipment for radiological protection, etc., so that disaster prevention officials can conduct disaster prevention activities accurately and safely at the site.

(b) Preconditions for development

Development of tele-operated robots and other technologies to enable nuclear disaster prevention workers to work in nuclear facilities, even in an accident at a nuclear power plant that may cause serious damage to the reactor core (e.g. multiple fuel breaks or core meltdown) and release a large amount of radioactive materials outside the plant (severe accident).

(c) Development objectives (basic plan)

(1) Working environment: High radiation (equivalent to 10 sV/h gamma rays or more) that is inaccessible to humans. In consideration of the worst-case scenario, the working environment should have 100%RH humidity, visibility without illumination due to loss of power supply, explosion-proof, waterproof and fire-proof. Also, fire occurrence should be considered.

(2) Moving function: Minimum width of the current nuclear power generation facility (0.8 m), overcoming steps, and ascending and descending stairs (inclination 40°).

(3) Power supply and communication: Communication between inside and outside should be possible by through penetration.

(4) Work: Various checks of the disaster situation, opening and closing of valves, cutting, drilling, opening and closing of doors, routing of hoses, transportation and installation of shielding, etc.

(5) The system should consider simplicity of operation, operation time of about 2 hours, common interface, etc.

(2) Lessons learnt and recommendations

(a) Practical application evaluation

A report on the evaluation of the practical application of nuclear disaster prevention support systems compiled in December 2002 concluded as follows (NUPEC, 2002):

> "In nuclear power facilities, the robot is expected to be used for surveying and monitoring the situation at disaster sites under high radiation, and for opening and closing some manual valves, etc.
>
> However, there are many issues that need to be improved, such as the slow walking speed compared to humans, the large width that makes it impossible to enter narrow places such as disaster sites under high radiation or places where manual valves are installed, and the short distance that can be travelled.
>
> (…). In the event of a disaster at a nuclear power generation facility or a reprocessing plant, it is thought that there will be few situations in which it can be used. However, if the equipment, performance, and use of the system are further improved in the future, and the issues that need to be improved are resolved, the system may well be used in the field during a nuclear disaster event."

E.1.3 Contribution to the Fukushima Daiichi nuclear accident recovery

(1) Information collection and work by robots

In the immediate aftermath of the Fukushima Daiichi accident, the primary mission was to stabilise the cooling system and contain the radioactive materials. After the cold shutdown, the focus shifted to removing the fuel from the spent fuel pools and extracting the fuel debris for decommissioning. However, the most important mission was, and still is, to reduce the radiation exposure of the workers who are performing various tasks at the site. Specifically, robots and remote-controlled devices are required for water injection, debris removal, survey (video acquisition, measurement of radiation dose, contamination distribution, temperature, humidity, oxygen concentration, etc.), sample collection, installation of measurement devices, decontamination, shielding and transportation of equipment, etc. Many robots and devices have already been introduced (Osumi, 2014; Asama, 2011a; 2011b).

The survey and operation robots that have been introduced are PackBot (see Fig. E.1.3) (2 units) manufactured by iRobot (United States); Quince (see Fig. E.1.4) developed by Chiba Institute of Technology, Tohoku University, International Rescue System (IRS), and New Energy and Industrial Technology Development Organization (NEDO), Quince 2 Quince 3, Warrior (see Fig. E.1.5) developed by iRobot (United States); Talon (QinetiQ (United States)), JAEA-3 (see Fig. E.1.6) developed by Japan Atomic Energy Agency (JAEA); Survey Runner (see Fig. E.1.7) developed by TOPY Industries, and a four-legged walking robot and a small travelling vehicle developed by Toshiba Corporation (see Fig. E.1.8); FRIGO-MA developed by Mitsubishi Electric Tokki System (see Fig. E.1.9); and an elevated work vehicle developed by AIST and Honda R&D (see Fig. E.1.10).

Figure E.1.3. Packbot

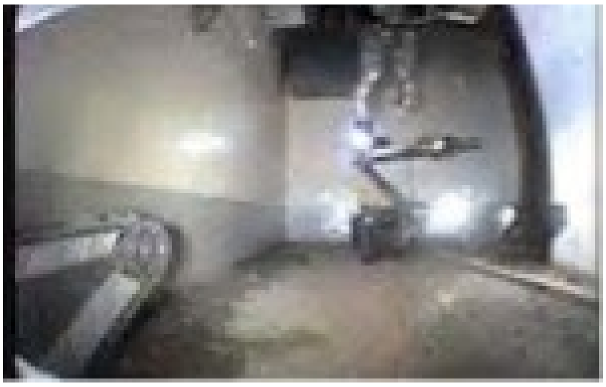


Figure E.1.4. Quince

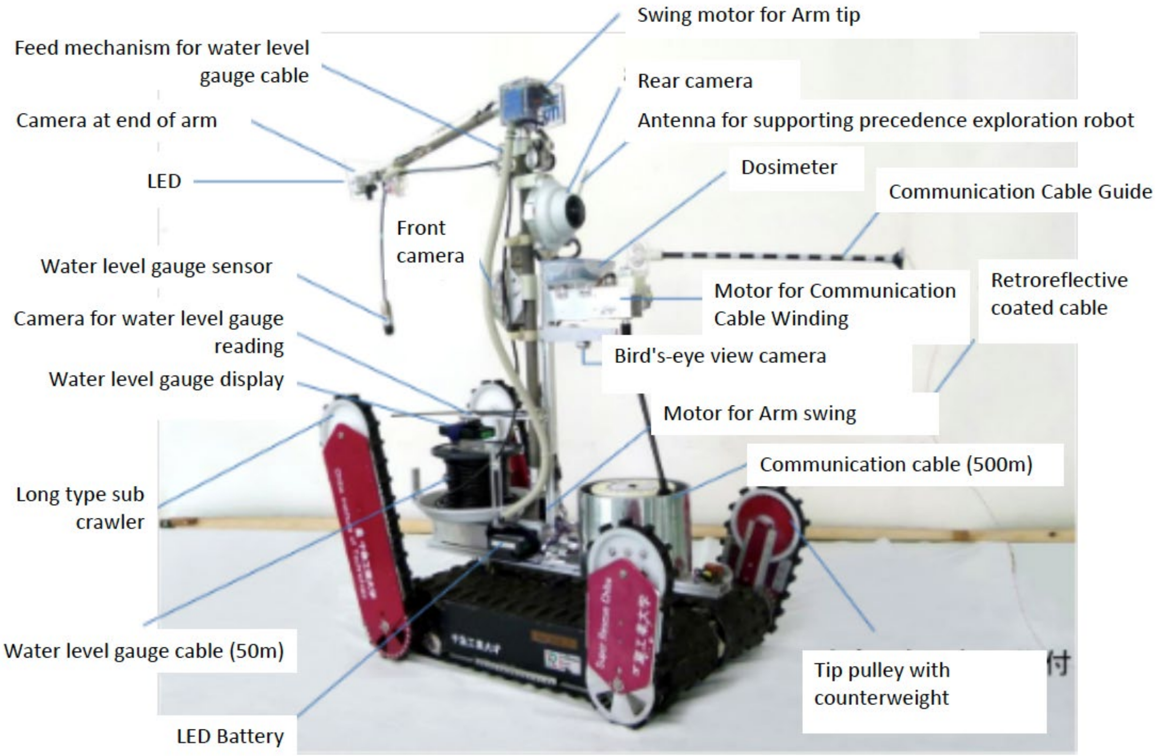


Figure E.1.5. Warrior

Figure E.1.6. JAEA-3

Figure E.1.7. Survey Runner

Figure E.1.8. Quadruped robot and small vehicle

Figure E.1.9. FRIGO-MA

Figure E.1.10. Elevated work vehicle

(2) Work with remote working machines

In the response to the accident at the Fukushima Daiichi Nuclear Power Plant and the decommissioning of the plant, the following unmanned construction equipment and other construction machinery are being used effectively:

a) Remote water injection by concrete pump truck

Immediately after the accident at TEPCO's Fukushima Daiichi Nuclear Power Station, the cooling of the reactors was the most important issue. As a means of stable water injection, remote water injection using a concrete pump truck was carried out in unit 4. A concrete pump truck manufactured by Putzmeister was installed and remotely operated (see Fig. E.1.11). For the remote operation, a light and a camera were installed at the end of the boom of the concrete pump truck, and the boom was remotely controlled by wireless LAN to ensure stable water injection while monitoring the camera images from the seismic isolation building.

Figure E.1.11. Remote water injection by concrete pump truck

b) Removal of rubble in nuclear power plants using unmanned construction machinery

Immediately after the accident, there was a lot of rubble generated by the tsunami and by the hydrogen explosion in the reactor building in the Fukushima Daiichi Nuclear Power Plant. In particular, the rubble generated by the hydrogen explosion had high radiation levels, which greatly hindered the work inside the power plant. Therefore, a joint venture (JV) of Taisei Corporation, Kajima Corporation, and Shimizu Corporation removed the rubble using unmanned construction equipment to reduce the exposure dose in the high-dose work environment (see Fig. E.1.12).

Figure E.1.12. Removal of debris using unmanned construction machinery

Specifically, several backhoes, crawler dump trucks (11 tonne), and camera trucks were used.

c) Removal of rubble inside the reactor building

Inside the reactor building of unit 3, remotely operated equipment was also used to remove rubble. The equipment used included Talon (manufactured by QinetiQ, United States) (see Figure E.1.13), Bob Cat (manufactured by QinetiQ, United States) (see Figure E.1.14), Brokk-90 (manufactured by Brokk, Sweden) (see Figure E.1.15), Brokk-330 (manufactured by Brokk, Sweden) (see Figure E.1.16). After that, ASTACO-SoRa (manufactured by Hitachi Engineering and Services, Ltd.), a remotely operated heavy machine, was used to remove obstacles such as rubble on the first floor of the unit 3 reactor building (see Figure E.1.17).

Figure E.1.13. Talon

Figure E.1.14. Bob Cat

Figure E.1.15. Brokk-90

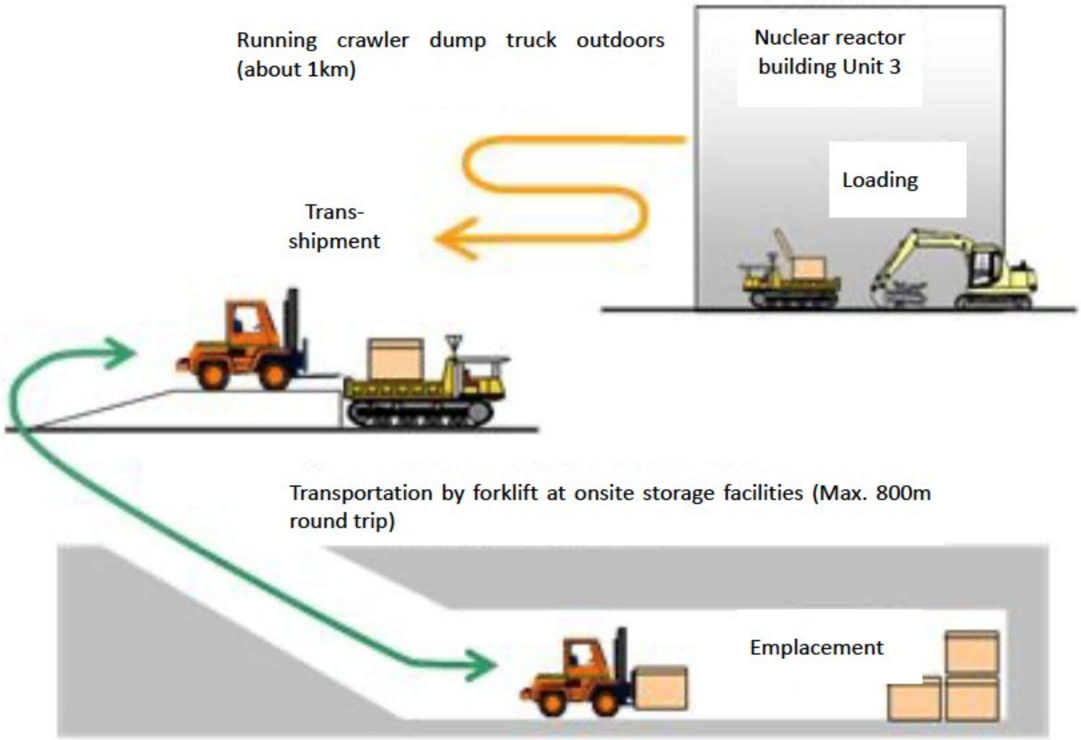
Figure E.1.16. Brokk-330

Figure E.1.17. ASTACO-SoRa

d) Removal and transportation of rubble from the top floor of the nuclear reactor building where a hydrogen explosion occurred.

The removal of the rubble from the top floor of the reactor building where the hydrogen explosion occurred is also being carried out using unmanned construction equipment. For the upper part of the reactor building of unit 4, the removal of debris was carried out by manned workers because the radiation level was low, but for the upper part of the reactor building of unit 3, the removal of rubble was carried out by remotely operated heavy machinery such as cranes and backhoes (Nipla) from the ground and platforms built around the reactor building in order to reduce the exposure dose to workers because the radiation level was high (see Figure E.1.18). In addition, Kajima Corporation has achieved fully automated transportation of high radiation level rubble from unit 3 using crawler dump trucks and forklifts.

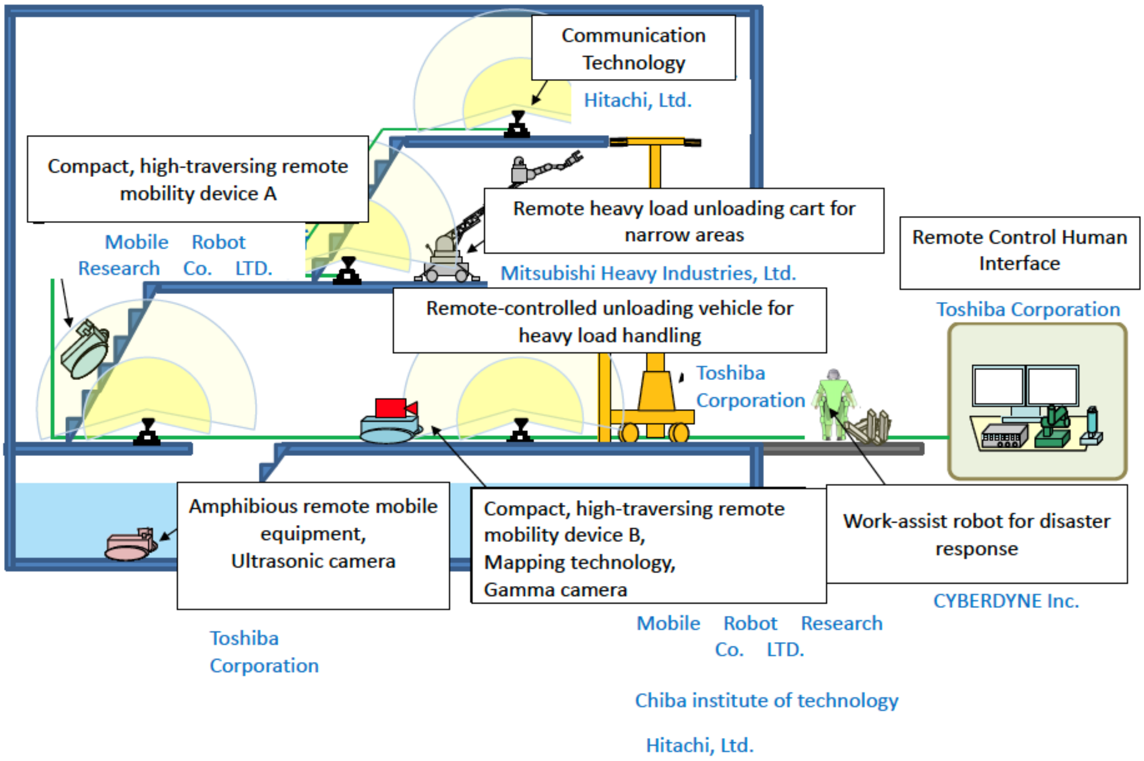
Figure E.1.18. Composition of automatic debris transport system



(3) Development of unmanned disaster response system

The Industrial Machinery Division of the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO) implemented the unmanned anti-disaster system R and D project as a common infrastructure technology for disaster response under the second supplementary budget for fiscal 2011, and developed the following (NEDO, 2012). Figure E.1.19 shows an overview of the project. These systems, equipment, and devices developed in this project are also planned to be used in the decommissioning of the Fukushima Daiichi Nuclear Power Plant.

Figure E.1.19. Conceptual diagram of the NEDO unmanned anti-disaster system R and D project



a) Development of work movement mechanism

A compact high-stepping remote handling device (see Fig. E.1.20 and E.1.21), communication technology (see Fig. E.1.22), remote-control human interface (see Fig. E.1.23), a remote heavy lifting/working cart in a narrow space (see Fig. E.1.24), and a heavy handling remote-control loading cart (see Fig. E.1.25) have been developed.

Figure E.1.20. Sakura

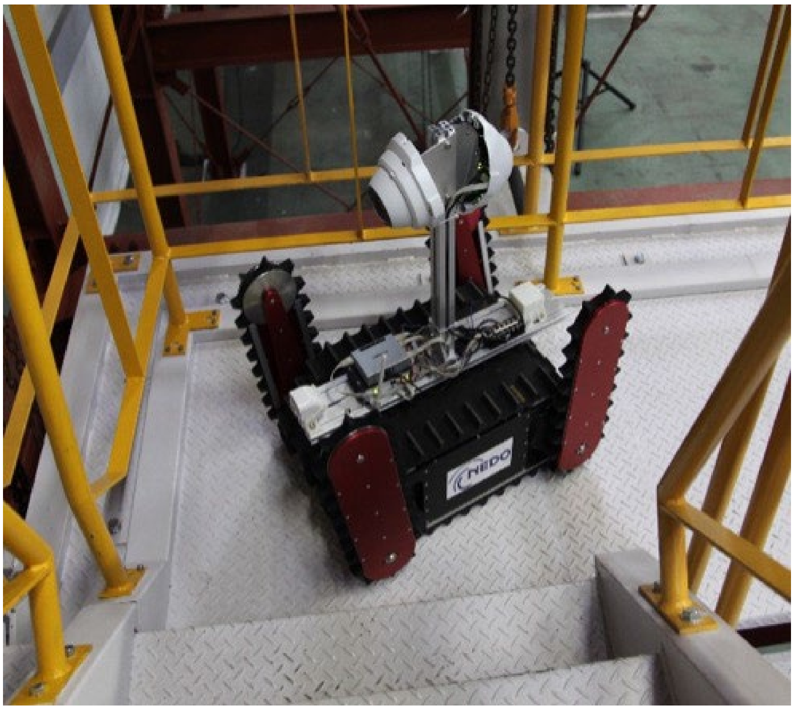


Figure E.1.21. Tsubaki

Figure E.1.22. Radio communication relay station

Figure E.1.23. Remote control human interface

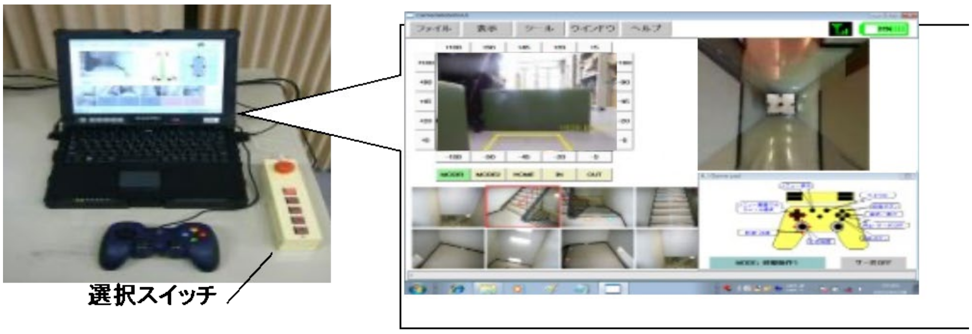


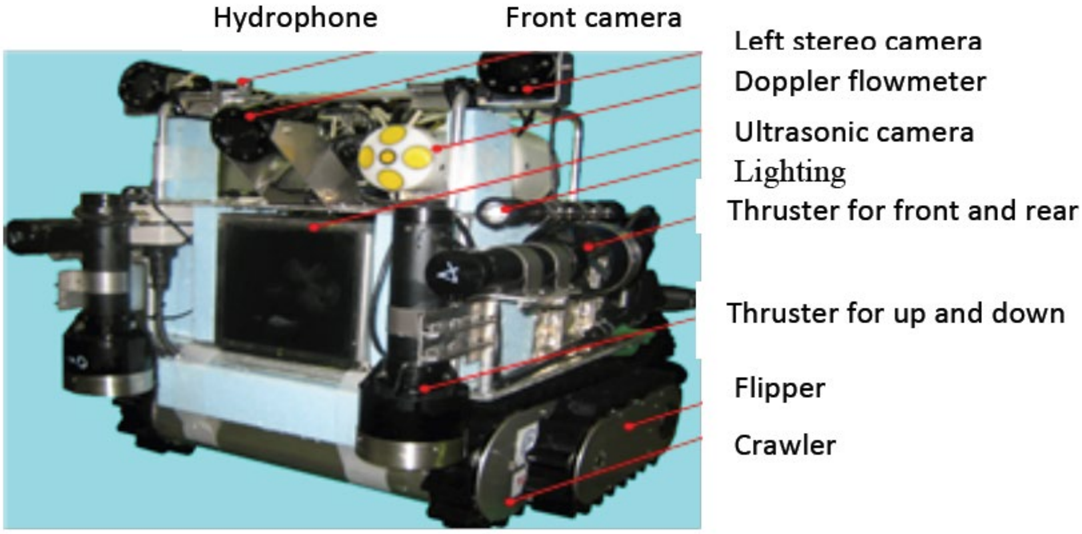
Figure E.1.24. Remote heavy load unloading cart for narrow areas (Super Giraffe)

Figure E.1.25. Remote-controlled unloading vehicle for heavy load handling (Super Lifter)

b) Development of measurement and work element technologies

Development and improvement of monitoring and handling devices for air and water (air monitoring device/water monitoring device (see Fig. E.1.26), pollution mapping technology, and handling device technology) was carried out.

Figure E.1.26. Amphibious mobile equipment



c) Development of work-assist robot for disaster countermeasures

A work-assist robot (see Fig.E.1.27) was also developed to reduce the workload of humans.

Figure E.1.27. Worker wearing a work-assist robot for disaster response

(4) Lessons learnt and recommendations

(a) Recommendations of the Industrial Competitiveness Council

In order to prepare for future disasters and accidents, it is necessary to analyse the problems that prevented the rapid and smooth introduction of robots and tele-operation equipment (Asama, 2011a; 2011b) when the Great East Japan Earthquake and the Fukushima Daiichi Nuclear Power Plant accident occurred, and to consider how to solve them.

In order to implement disaster response robots in society, the Industrial Competitiveness Council conducted the "Disaster Response Robots and Operation Systems" project from 2011 to 2012 (COCN, 2011; 2012). This can be summarised in the following three main points:

(1) Research and development bases and projects (hardware recommendations)

There are many technical issues that need to be developed to enable robots to be used in various types of disasters, including technologies for movement and access to special environments, stable communication for tele-operation, spatial awareness for tele-operation, autonomous and intelligent technologies to improve operability, and measurement technologies and inspection, diagnosis, and maintenance technologies.

There are many technological issues to be developed. This needs to be addressed through needs-driven basic technology research and advanced practical application research. In addition, it is effective to hold competitions and challenges such as the DARPA Challenge (DARPA, 2017) in order to advance the solution derivation and systemisation technologies.

(2) Disaster Prevention Robot Center (recommendations on infrastructure)

It is necessary to establish a disaster prevention robot centre with the following functions: demonstration tests, operator training, functional evaluation and certification of explosion resistance, release resistance, durability, and safety; accumulation, centralised management, and provision of robot technology information; and emergency response.

For demonstration tests and operator training, it is essential to set up test fields and mock-ups for these functions.

(3) Strategy formulation, standardisation, and institutional design (software-related proposals)

It is important to ensure the long-term sustainability of the development and operation of disaster response robots, and strategies for this purpose must be designed and formulated. In addition, it is also important to design a system that includes standardisation activities for functional evaluation and interface specifications of robots, deregulation, strengthening of regulations (e.g. mandatory deployment), formulation of taxation systems such as tax exemptions, and improvement of the environment including securing radio frequencies and insurance systems.

(b) Recommendations for the future

In contrast to the so-called "robots" that were not introduced quickly at the time of the disaster, unmanned construction machines were introduced and used at the site at a very early stage. There is a reason for this. The unmanned construction technology was developed and applied when Mt. Unzen Fugen erupted in 1991, causing great damage due to pyroclastic flows and mud and stone flows, and is still used in the construction. The unmanned construction technology has been used frequently in various hazardous operations, such as rescue work at the site of a tunnel landslide during the Niigata Chuetsu Earthquake in 2004 and construction of a landslide dam caused by Typhoon No. 12 in 2011. It is a technology with a proven track record that has been used in various hazardous operations. The fact that this technology has been used continuously at various sites is considered to be an important factor in the rapid introduction of this technology during the nuclear accident. In order to ensure that robots can also be deployed smoothly in the event of a disaster, this should be used as a model.

In order to be able to quickly deploy robots in the field in response to future disasters, it is necessary to:

(1) Conduct needs-driven research and development, and actively involve and participate in the development of robot users, such as firefighters, police, defence, local governments and electric power companies

(2) Develop a practical platform that can be used in the field, and to operate it during normal times, including training.

(3) The national and local governments should take the initiative in supporting the practical application and operation of the system to enable the participation of companies, and create demand by procuring the system or requiring its deployment.

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E.2 Canada: COG-MDA strategic R&D study on decommissioning robotics

E.2.1 Introduction

The COG-MDA study on robotics and automated systems is part of an ongoing and larger effort being pursued by CANDU Owners' Group (COG) Decommissioning and Long-Term Waste Management (DLTWM) Program to identify key technologies or processes that can lead to significant savings throughout the CANDU decommissioning life cycle. This strategic R&D study and stream of inquiry is focused on determining for which tasks it is economically viable (i.e. tasks that would result in a positive return on investment (ROI) if an investment in technology is made) to use robotics and automation during decommissioning. A set of drivers and scoring criteria were defined to permit the systematic evaluation of planned CANDU decommissioning tasks, which resulted in a subset of high-prospect areas that would benefit from the application of robotics (see details in Section E.2.2).

Table E.2.1 summarises the multiple phases proposed for this project, where Year 1 corresponds to Fiscal Year 2018-19 in COG's calendar.

Table E.2.1. COG-MDA decommissioning robotics project workflow (2018-present)

Year 1	Year 2	Year 3	Year 4 (ongoing)
• Systematic Process Evaluation based on Existing Decommissioning Plan(s) • State-of-the-Art Assessment • Selection of Top Robotic Solution Candidates	• Cost-Benefit Analysis (CBA) Case Studies based on Top Candidates	• Conceptual Engineering • Sub-tier Technology Roadmap • Additional CBA and ROI Calculations	• Short-Term Technology Demonstration Plan • Higher fidelity CBAs • Additional Concepts for Robotic Candidates • Work with Utilities to Update Decommissioning Cost Estimates (e.g. ISDC Level-3)

Part of the ongoing R&D scope involves investigating robotic solutions with short-term (5-year) ROI in more detail, such as automated mobile platforms for comprehensive characterisation and surveillance of nuclear power plants. Typically, a complete characterisation occurs in the early stages of decommissioning, prior to safe storage (post-shutdown). Additional surveys are conducted through inactive dismantlement, dismantlement of nuclear components, site clean-up and site clearance. The COG-MDA study also recommended integrating robotics and automation with emerging digital asset management solutions to generate an even greater ROI. Leveraging advances in computing, artificial intelligence (AI), building information models (BIMs), mixed reality and data fusion, it is possible to enable automated digitisation of nuclear power plant assets during decommissioning, including the development of three-dimensional (3-D), semantically-enriched BIMs to support job planning and decision making throughout all decommissioning phases.

E.2.2 Decommissioning process evaluation

In 2019, MDA conducted a systematic evaluation of the CANDU decommissioning life cycle and identified the top areas for investment. An existing preliminary decommissioning plan (PDP) corresponding to the Pickering Nuclear Generating Station (PNGS) located in Ontario, Canada, was used as a reference to generate a high-level task breakdown. MDA extracted approximately 78 decommissioning tasks from the PDP for analysis, and a subset of 20 tasks were identified as good prospects for robotics and automation implementation.

The 20 high-value decommissioning activities were selected by qualitatively assessing the operating environment, existing approaches (conventional/manual methods), state-of-the-art technology readiness, and the potential cost-benefit obtained from robotics and automation versus using conventional tools/machinery for task execution.

E.2.2.1 Scoring methodology

In total, six independent characteristics of CANDU decommissioning were chosen to systematically score the tasks extracted from the existing PDP, as follows:

a) Radiological waste classification (low-, intermediate- or high-level wastes)

b) Contaminated waste mass segregation

c) Hazardous waste classification (mixed or non-radiological)

d) Cost estimates based on the International Structure for Decommissioning Costing (ISDC) Level 2

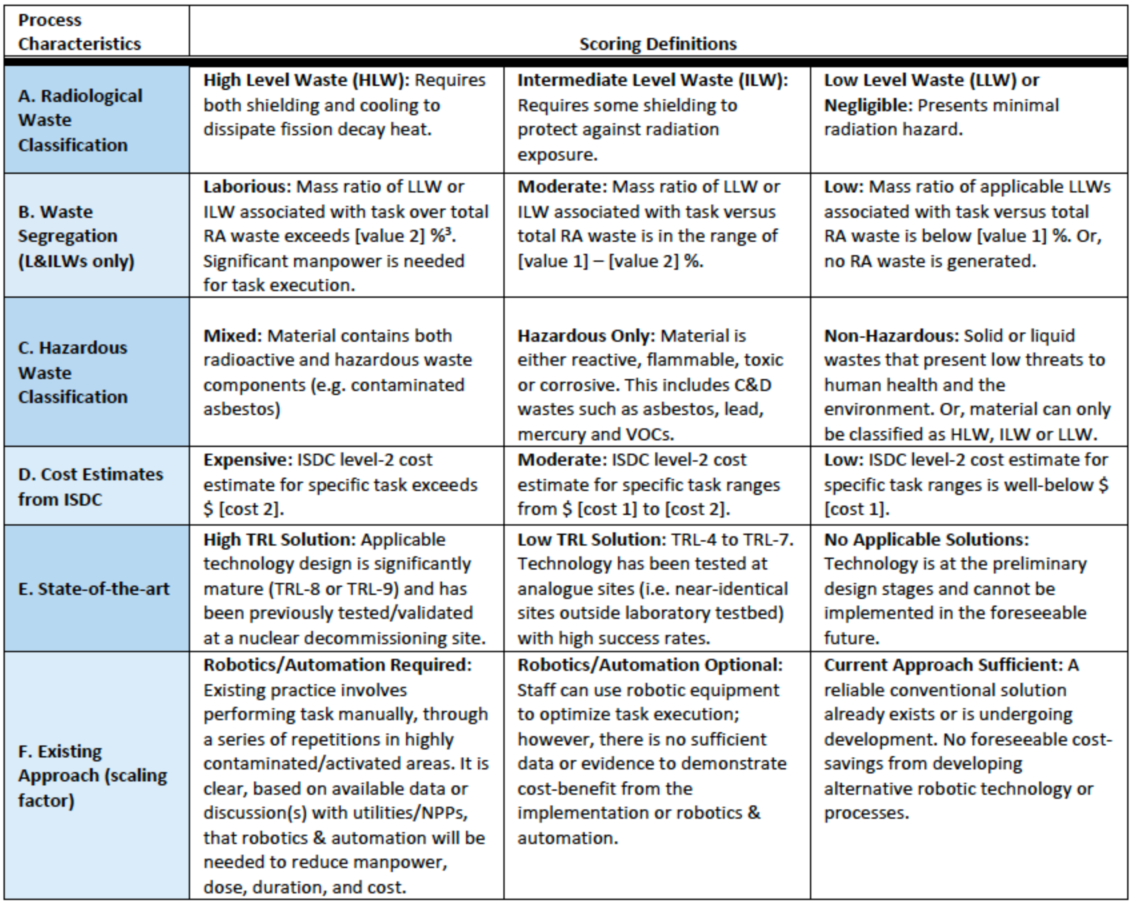
e) State of the art

f) Existing approach (used as a weighing factor)

Based on the waste-inventory and costing data available at the time of the analysis, strong emphasis was placed on the Radiological Waste Classification, ISDC Level-2 Cost Estimates and state-of-the-art technology readiness characteristics. For initial scoring purposes, the costs allocated to the PDP tasks were based on the existing ISDC Level-2 benchmark cost breakdown for CANDU sites in Canada and Europe.

Table E.2.2 contains the scoring definitions assigned to each characteristic used for systematic evaluation of CANDU decommissioning tasks, where the reference values (e.g. upper/lower score limits) are omitted here for generalisation purposes.

Table E.2.2. Preliminary decommissioning plan process-task evaluation characteristics.



Process Characteristics	Scoring Definitions		
A. Radiological Waste Classification	**High Level Waste (HLW):** Requires both shielding and cooling to dissipate fission decay heat.	**Intermediate Level Waste (ILW):** Requires some shielding to protect against radiation exposure.	**Low Level Waste (LLW) or Negligible:** Presents minimal radiation hazard.
B. Waste Segregation (L&ILWs only)	**Laborious:** Mass ratio of LLW or ILW associated with task over total RA waste exceeds [value 2] %[3]. Significant manpower is needed for task execution.	**Moderate:** Mass ratio of LLW or ILW associated with task versus total RA waste is in the range of [value 1] – [value 2] %.	**Low:** Mass ratio of applicable LLWs associated with task versus total RA waste is below [value 1] %. Or, no RA waste is generated.
C. Hazardous Waste Classification	**Mixed:** Material contains both radioactive and hazardous waste components (e.g. contaminated asbestos)	**Hazardous Only:** Material is either reactive, flammable, toxic or corrosive. This includes C&D wastes such as asbestos, lead, mercury and VOCs.	**Non-Hazardous:** Solid or liquid wastes that present low threats to human health and the environment. Or, material can only be classified as HLW, ILW or LLW.
D. Cost Estimates from ISDC	**Expensive:** ISDC level-2 cost estimate for specific task exceeds $ [cost 2].	**Moderate:** ISDC level-2 cost estimate for specific task ranges from $ [cost 1] to [cost 2].	**Low:** ISDC level-2 cost estimate for specific task ranges is well-below $ [cost 1].
E. State-of-the-art	**High TRL Solution:** Applicable technology design is significantly mature (TRL-8 or TRL-9) and has been previously tested/validated at a nuclear decommissioning site.	**Low TRL Solution:** TRL-4 to TRL-7. Technology has been tested at analogue sites (i.e. near-identical sites outside laboratory testbed) with high success rates.	**No Applicable Solutions:** Technology is at the preliminary design stages and cannot be implemented in the foreseeable future.
F. Existing Approach (scaling factor)	**Robotics/Automation Required:** Existing practice involves performing task manually, through a series of repetitions in highly contaminated/activated areas. It is clear, based on available data or discussion(s) with utilities/NPPs, that robotics & automation will be needed to reduce manpower, dose, duration, and cost.	**Robotics/Automation Optional:** Staff can use robotic equipment to optimize task execution; however, there is no sufficient data or evidence to demonstrate cost-benefit from the implementation or robotics & automation.	**Current Approach Sufficient:** A reliable conventional solution already exists or is undergoing development. No foreseeable cost-savings from developing alternative robotic technology or processes.

E.2.2.2 State-of-the-art assessment

In parallel to the decommissioning process evaluation, a state-of-the-art assessment of applicable robotic and automation technologies with different technology readiness levels (TRLs) and previous mission legacy was conducted. MDA scored approximately 80 commercial off-the-shelf technologies in 11 technology categories. Approximately 23 technologies were identified as having direct-applicability to CANDU decommissioning activities and were later used as references in the conceptualisation of robotic solutions for detailed cost-benefit analysis (CBA).

Table E.2.3 shows a summary of all 11 robotic categories investigated in the COG-MDA study, and the evaluation criteria used to select the top candidates per category.

Table E.2.3. Summary of robotic categories and technology evaluation criteria.

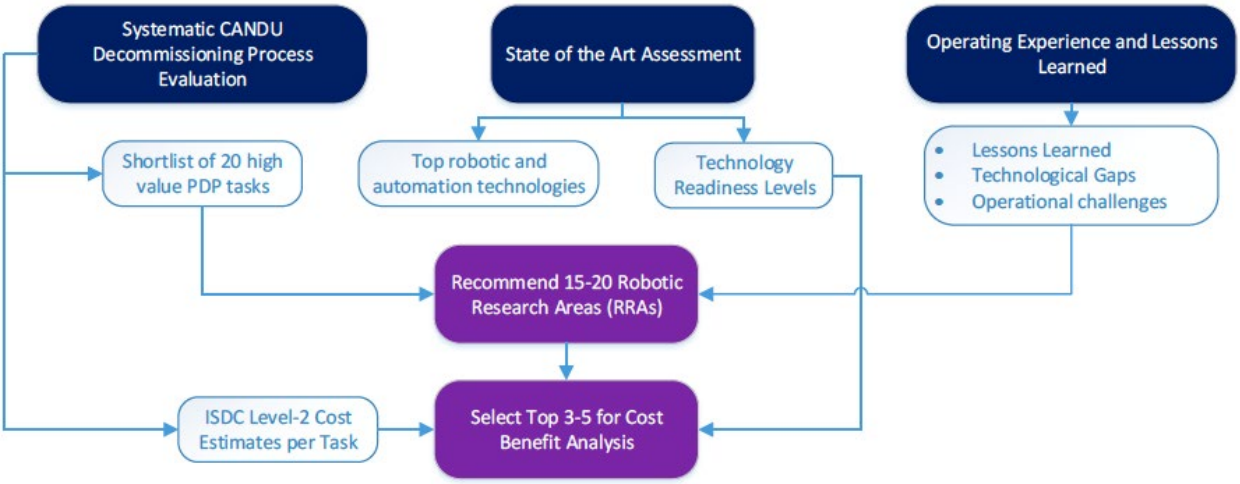
ID	Robotic Categories	Evaluation Criteria
1	Decontamination	➢ Direct Applicability ➢ Technology Readiness ➢ Deployability ➢ Recoverability ➢ Versatility ➢ Mission Heritage
2	Dismantling & Demolition	
3	Biomimetic	
4	Humanoid Robotics	
5	Crane Systems	
6	Robotic Arms / Manipulators	
7	Tactical Robots / Crawlers	
8	Transportation	
9	Unmanned Aerial Vehicles (UAVs)	
10	Remotely Operated Underwater Vehicles (ROVs)	
11	Waste Management Systems	

E.2.3 Proposed robotic research areas

The results from the systematic CANDU decommissioning needs assessment, state-of-the-art assessment, and lessons learnt from global robotic deployments (i.e. relevant operating experience/OPEX) were consolidated and used to formulate a list of 12 robotic and automation solutions with high prospect for investment. In the COG-MDA study, these high-value solution candidates are referred to as "robotic research areas" (RRAs), and were further categorised as short-, medium- and long-term solutions depending on their expected development and deployment time frames (i.e. in anticipation of the decommissioning of CANDU facilities in Canada).

Figure E.2.1 illustrates the approach followed to recommend a subset of high-value RRAs for cost-benefit analysis and conceptual engineering design.

Figure E.2.1. Systematic selection approach of robotic research areas for application to decommissioning.



E.2.4 Cost-benefit analysis (CBA)

The goal of cost-benefit analysis (CBA) is to generate high-fidelity estimates of potential savings from implementing a robotic or automated solution, versus using a conventional approach during decommissioning (e.g. manual segmentation or manual site characterisation). The CBA scenarios provide a sequential mapping of the robotic/automated system deployment and operational steps, including task execution and equipment demobilisation. Subsequently, the task-execution savings obtained via quantitative analysis, and the anticipated costs of development and deployment, are used to calculate short or long-term return on investment (ROI) estimates for the top robotic technology candidates.

The CBAs must provide a time-based, step-by-step comparison between the numerical attributes (e.g. dose uptake, manpower-hour and task-execution duration) associated with the robotic and conventional approaches. These quantitative analyses must also account for the potential hazards and operational challenges posed by the remaining radiological activity on site, as well as infrastructure/geometrical constraints that might limit accessibility.

The savings corresponding to each CBA study were calculated for 3 key numerical attributes, as follows:

- manpower-hour;
- cumulative radiation dose per task;
- task duration for critical-path and parallel activities.

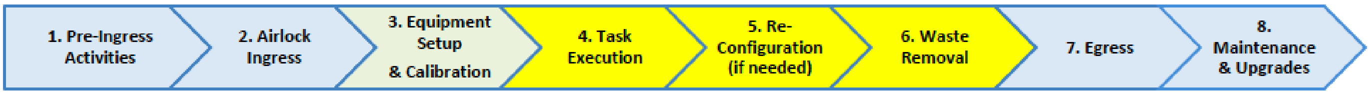
E.2.4.1 Conventional vs. robotic process mapping

As most CANDU reactors in Canada undergoing decommissioning are currently very early in the process (e.g. at the “safe storage with surveillance” stage), some assumptions about the dismantling activities and equipment used during later stages were made based on analogue processes (e.g. outages or refurbishment campaigns, where reactor components are typically removed and replaced).

MDA leveraged existing datasets containing timestamped dose and radionuclide activity values, as well as storyboards and outage-inspection reports to re-construct a mapping of conventional decommissioning processes. This mapping must capture the entire sequence of manual operation steps; from equipment ingress to setup, and from task execution to waste removal and egress. Subsequently, an equivalent concept of operations was developed for the proposed robotic candidate(s), mapped in parallel with the conventional (manual) task-execution steps.

Figure E.2.2 shows a generic operational flowchart, showing the sequence of robotic operations inside a nuclear reactor vault.

Figure E.2.2. Simplified process flowchart for robotic and automation operations inside the vault.



E.2.5 Radiological decay considerations

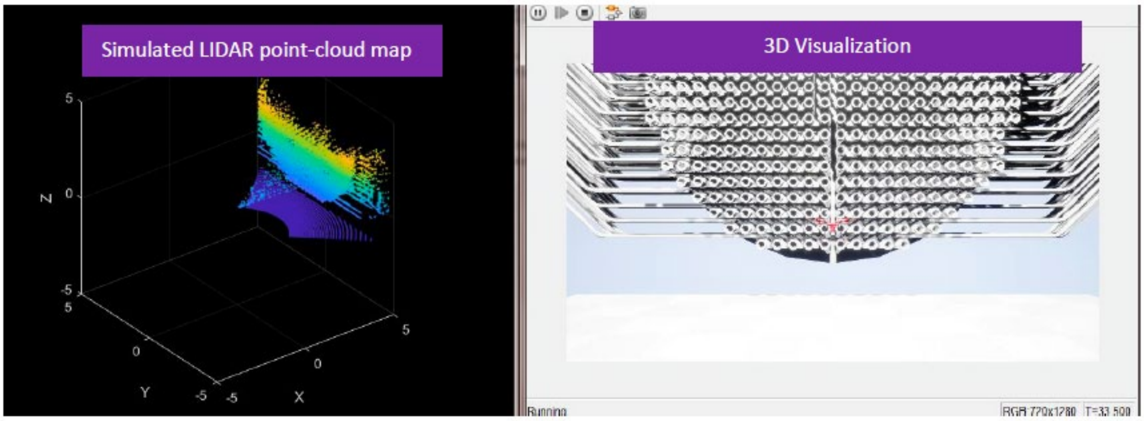
When the cost savings are driven primarily by dose uptake, it will be necessary to account for the decay of radionuclide activity throughout the robot’s operational life cycle. Exceptions include technologies that are not reusable (one-time use solutions). As such, the cumulative dose associated with direct exposure to contaminated material becomes a temporal variable in the cost-benefit analysis.

MDA leveraged characterisation reports and in situ radiation surveys conducted during previous CANDU outages to get an approximate mapping of dose and radionuclide activity that the robot (or human) may be exposed to at any given time following shutdown of a CANDU site. Therefore, the CBA results in the COG-MDA study are presented as decay-corrected cost savings, which account for the reduction in radiation based on the length of the safe storage period.

E.2.6 Robotic simulations

For some case studies outlined in the work package for decommissioning robotics, detailed Computer-Aided Design (CAD) models of plant infrastructure were used in combination with time-based robotic simulations to obtain more realistic estimates of savings and a three-dimensional visualisation of the operations. These 3-D simulation environments can be used in the future for design verification, training and mission planning. Figure E.2.3 shows an example of a simulated drone campaign developed by MDA for routine radiation survey and characterisation of CANDU sites during safe storage.

Figure E.2.3. Robotic simulation of a UAV for complete radiation mapping during safe storage with surveillance.



Source: MDA

E.3 United Kingdom’ approach to regulating robotics and autonomous systems

E.3.1 Background

E.3.1.1 The UK regulatory framework

The legal framework for the regulation of the UK nuclear industry is based around the Health and Safety at Work Act 1974 (UK Government, 1974), the Energy Act 2013 (UK Government, 2013), the Nuclear Installations Act 1965 (UK Government, 1965), and Ionising Radiations Regulations 2017 (UK Government, 2017) and Nuclear Industries Security Regulations 2003 (UK Government, 2003). The UK Energy Act 2013(UK Government, 2013) establishes the Office for Nuclear Regulation (ONR) as the UK independent nuclear regulator for safety, security and safeguards. The legal requirement set in legislation (UK Government, 1974, 2013) is for the UK dutyholders to reduce the health and safety risk from their nuclear activities to workers and the public as low as reasonably practicable (ALARP). The key principles used by ONR inspectors in its regulation of safety and security in nuclear facilities are set out in the ONR safety assessment principles (SAPs) (ONR, 2020a) and security assessment principles (SyAPs) (ONR, 2017).

The regulatory regime outlined above is predominantly goal-setting, in that it focuses on risk and on outcome rather than prescribing design solutions or compliance with standards which often lag behind the development of new technologies. Also, the regulatory regime can be considered as technology-neutral so it provides a constructive environment within which innovation can thrive, but which ensures the basis for safety and security is clearly understood and communicated. Using an enabling regulatory philosophy, ONR aims to work with the UK nuclear industry to realise the benefits of new technology and novel approaches, providing a progressive, regulatory environment.

E.3.1.2 UK Nuclear Sector Deal and the role of regulators

In 2018, the UK government published its Nuclear Sector Deal (UK Government, 2018), which identifies innovation and the use of new technology as a means of accelerating risk reduction at nuclear facilities, particularly at legacy plants and in reducing decommissioning costs. Responsibility for many of the changes and initiatives prompted by the Nuclear Sector Deal will be delivered by the nuclear industry.

However, a 2019 paper on the regulation of the fourth industrial revolution (UK Government, 2019) recognises the key role played by regulators. Regulatory processes are often cited as a barrier to innovation, with a perception that regulation is inevitably risk-averse, regulators will be reluctant to accept novel techniques or approaches, or that the regulatory processes associated with new technologies must be long and complex. To address this challenge, the UK government (2019) outlines how regulators need to be open to discuss innovative ideas to ensure that regulatory processes, procedures and behaviours do not stifle creative thinking or create unnecessary barriers.

Early engagement with industry and the supply chain is a priority, fostering an environment that facilitates innovation through clear understanding of common goals and how these may be achieved. Continuous improvement of regulatory processes can also help remove unnecessary bureaucracy while keeping them fit for purpose and robust. This needs to be achieved while maintaining regulatory independence, which is essential in effectively delivering appropriately balanced judgements.

E.3.2. Approach to innovation in the UK nuclear industry

E.3.2.1 Enabling innovation

Recognising the ambitions in UK Government (2018) and the expectations in UK Government (2019), ONR published in 2020 a guidance document setting out the approach to regulating innovation (ONR, 2020b). This document outlines a regulatory approach that is enabling, accessible, open-minded, poses appropriate challenge, works collaboratively, and yet is adaptable and responsive to the needs of industry / innovators and the wider environment. An example of how this is achieved is ONR's engagement with a wide range of stakeholders, both nationally and internationally, to facilitate the discussion and implementation of innovative solutions. Rather than being a barrier to innovation, as a modern progressive regulator, ONR (2020b) outlines how ONR is committed to regulating in a way that encourages and facilitates technological advancements, providing adequate justifications are in place that nuclear operations will be adequately safe and secure (ONR, 2020b). To achieve this, ONR promotes constructive dialogue at an early stage with dutyholders, providing early feedback on the licensing challenges of candidate options, avoiding surprises and building trust which will improve communication.

In implementing the principles in ONR (2020b), ONR continuously reviews the suitability of its regulatory approach and remain responsive to the need for innovation in the nuclear sector. ONR also incorporates regular horizon scanning, which aims to understand future use of new technologies in nuclear applications, providing the foresight to prepare for developments by building internal capability (ONR, 2018, 2020b).

E.3.2.2 Regulating innovation in practice: robotics and autonomous systems

An example of an area where this approach to regulating innovation is adopted by ONR is the permissioning of activities involving robotics and automation system (R&AS) solutions. While recognising the benefit of R&AS in reducing the radiological risks and normal operation exposure of workers by remote operations, ONR is also conscious of the new safety and security challenges introduced by R&AS technologies, for example due to their complexity (e.g. new failure modes and potential cyber attack vectors) and limited experience of previous deployment in nuclear applications

In this context, ONR's aim is to ensure the regulatory system continues to be flexible and outcome-focused by delivering targeted training programmes to help ONR inspectors understand innovation and influence positive improvement in both nuclear safety and security of robotic systems. A number of initiatives have been taken forward by ONR to promote this, including:

- engaging at early stages with dutyholders to understand the challenges, provide initial feedback and work on enablers / blockers for a safe and secure implementation of R&AS;
- proactively reviewing the adequacy of ONR's guidance in response to new technological solutions such as R&AS;
- building key links with stakeholders in research, academia, and industry to better understand the technological and industry development needs;
- commissioning research in areas where additional internal knowledge needs to be gained to regulate the industry;
- engaging internationally (e.g. with the IAEA, NEA and other peer regulators) to promote consistency in the outcomes, and share good practices.

E.3.2.3 Addressing innovation challenges with R&AS

Early experience in applications of robotic solutions in the UK nuclear industry involved their use in non-safety applications. Projects are currently under way to trial innovative technologies on nuclear licensed sites in pilot projects called "demonstrators", to test new concepts for delivering safety functions in a safe environment, before deployment in larger projects/live applications. A few examples of early learning and areas of future interest in the area of R&AS are presented below:

- Cross discipline engagement: this recognises that the use and substantiation of R&AS involves multiple disciplines (both from ONR and dutyholder organisations) and its complexity in providing or supporting an overall safety function cannot be dealt with separately within each specialism. Typical disciplines involved include, but are not limited to, human factors, fault studies, internal hazards, instrumentation and control, mechanical engineering and cyber security. This aspect is particularly important in the UK regulatory context where the legal requirement to reduce the risk ALARP needs to holistically consider various disciplines in the context of the overall substantiation. Engagement of various stakeholders (including the regulator, as appropriate) and disciplines at early stages in the design process has proved to be particularly valuable, e.g. in identifying design / operational requirements and in promoting fail-safe / secure-by-design principles.
- Screening of options (or "optioneering"): this requires discussions at early stages of various options / alternatives and documentation of the outcome of the decision-making process. In early discussions on R&AS, optioneering was recognised as a key enabler. The result of this process becomes useful also at later stages of the design and licensing process, to confirm the rationale for specific design choices and also to articulate how the risk of the proposed solution is reduced ALARP.
- Substantiation of commercial off-the-shelf (COTS) solutions: many proposed applications of R&AS involve the modification and deployment of commercial off-the-shelf equipment, i.e. equipment not initially developed for nuclear applications. The substantiation of COTS solution can be challenging for a number of reasons, including access to key proprietary information from the manufacturers. Future work is planned in this area, to identify proportionate and pragmatic approaches for the substantiation of R&AS, graded to the safety class / reliability target.
- Co-operative working between industry/academia/regulator: there is currently a significant effort on R&AS across various industries and stakeholders (academia, regulators, other technology clusters). Early experience showed the value of having broad representation from across the sector and supply chain within relevant forums to discuss common challenges and find synergies, avoiding duplication of effort or inconsistent approaches and early engagement with regulators. An example of this joint effort is the Robotics and Artificial Intelligence in Nuclear (RAIN) hub (RAIN, 2021), which is facilitating discussions between academia, licensees and relevant regulators in several technical areas. Other discussions are ongoing with health and safety regulators in non-nuclear sectors (e.g. Health and Safety Executive), and independent bodies such as the Nuclear Innovation and Research Office (NIRO).
- Targeted research: early experience showed that areas where uncertainty in the capabilities of new technology to perform safely and securely can be a significant concern and this needs to be addressed by targeted research to underpin claims made by users and thereby enable the deployment of R&AS in nuclear. Examples of these areas includes artificial intelligence and machine learning tools that can be an essential element of autonomous systems. Their safe and secure application in the nuclear industry requires, among other things, increasing the competence of key organisation in this area and targeted research.

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