Best Practice Guidelines and Lessons Learned from Robotic System Deployment in Nuclear Decommissioning

Howard Chapman, John-Patrick Richardson, Colin Fairbairn, Antonio Di Buono, Andrew Gale

Introduction

The UK National Nuclear Laboratory (UK NNL) has a proven track record of delivering the deployment of robotic solutions for nuclear decommissioning at the Sellafield site with a description of the typical challenges faced and strategies being adopted outlined in [1].

This paper provides a high level overview of robotic deployment at the Sellafield site and provides an appreciation of the generic challenges and constraints commonly encountered during nuclear decommissioning. The findings from a review of a number of mid Technology Readiness Level (TRL) robotic projects undertaken by UK NNL are examined and lessons learned are identified to provide a common reference framework allowing success for future robotic projects to be optimised. TRLs represent a scale of technology readiness from 1 (blue sky research) to 9 (industrial application) established by the National Aeronautics and Space Administration (NASA). Mid-TRL stages are 4-6, including the development and testing at small to large scale, prior to 'inactive commissioning' (i.e., Stage 7) [2].

The aim is to identify common challenges to the deployment of robotic technologies for nuclear decommissioning in the UK. This approach will help to build an improved methodology and identify best practice guidelines for stakeholders; whilst assisting innovation in this area. This will help to accelerate decommissioning programmes and strategic objectives. This will also help to build stakeholder confidence in robotic solutions and help to convince end users to adopt these technologies to reduce overall project costs.

Regulation and Legal Requirements

As detailed in [3];

"The civil nuclear industry worldwide is regulated to ensure that activities related to nuclear energy and ionising radiation are conducted in a manner that adequately protects people, property and the environment [4].

In the UK, the Office for Nuclear Regulation (ONR) is the agency responsible for the licensing and regulation of nuclear installations. The legal framework for the UK nuclear industry is based around the Health and Safety at Work Act 1974 (HSWA) [5], the Energy Act 2016 [6], and the Nuclear Installations Act 2016 (NIA)[7].

A fundamental requirement cited in the legislation is that risks be reduced to "As Low As Reasonably Practicable" (ALARP). This principle provides a requirement to implement proportionate measures in order to reduce risk, where doing so is reasonable. The ALARP principle is applied by adhering to established good practice, or in cases where this is unavailable, it is applied to demonstrate that measures have been implemented up to the point where the cost of additional risk reduction is disproportionate to the benefit gained [8]".

The ONR uses a list of Safety Assessment Principles (SAPs) [9] and supporting Technical Assessment Guides (TAGs) to guide regulatory decision making in the process of granting permissions.

The European Union (EU) formulates general safety objectives via a large number of directives, (circa 30 active directives currently available). However, only a small selection of directives are relevant to a typical machine builder and the safety objectives are more precisely specified through standards [10]. The standards have no direct legal status on their own until they are referenced in domestic laws and regulations. In practice manufacturers of robotic Commercial off the Shelf (COTS) equipment use the "Conformité Européenne" (CE) mark to document the fact that all relevant European directives have been applied, and appropriate conformity to all assessment procedures have been achieved. The UK

Conformity Assessed (UKCA) is the new conformity marking to be used in the UK in place of the CE mark following Brexit [11].

Based on the European Parliament and Council of the European Union Machinery Directive 2006/42/EC [12], a robot system, which can be considered to be general machinery for use at a site of decommissioning, falls within the scope of the Machinery Directive 2006/42/EC and the Supply of Machinery (Safety) Regulations 2008 [11]. Nuclear sites are not exempt with respect to these regulations. This means that robot systems require CE marking, or UKCA equivalent. The person placing the machine into a specific application is known as the 'integrator' and must perform the conformity assessment procedure to conclude a 'Declaration of Conformity' [10], or UKCA equivalent. The UKCA marking is a supplier statement that the machinery is regarded by the supplier to be safe for use, for the purpose for which it is supplied; providing to the end-user a clear indication to that effect. Compliance with the regulations requires only that a supplier or manufacturer demonstrates equipment to be safe to use and to satisfy that supplier's quality assurance procedures. It should, therefore, not be regarded as additional work or optional. It should be considered part of the actual product or equipment.

Requirements for Robotic Deployment at Sellafield Site

In the UK, many nuclear installations including those at Sellafield site were not constructed with decommissioning in mind. This presents a number of constraints for robotic decommissioning deployment, but also an opportunity to demonstrate their effectiveness. Existing normal operations require personnel to undertake tasks manipulating plant and equipment, deploying tooling in close proximity to contaminated and other hazardous radioactive material [13]. By undertaking these tasks, personnel are often in close proximity to contaminated material with the potential for radiological dose uptake, through direct exposure, internal dosing and wounds.

It is recognised that the possible future deployment of robot systems, offering a higher degree of Human Robot Collaboration (HRC), could help Sellafield site achieve the Nuclear Decommissioning Authority's (NDA) Grand Challenge aspiration to provide a 50 % reduction in decommissioning activities carried out by humans in hazardous environments by 2030, in order to reduce risk and improve productivity through more efficient use of robotic equipment[14]. Successful delivery of the Sellafield site mission relies on the availability of a sustainable waste management infrastructure. The future deployment of robot systems, in particular those offering a higher degree of HRC, will reduce risk; and improve productivity through more efficient use of robotic equipment.

As detailed in [15], a selection of key areas where technology development opportunities exist are:

- "Waste processing using autonomous size reduction offering 24 hours, 7 days per week sort and segregation with robotic enhanced waste packing to increase productivity and reduce waste packages and volume of storage. This would comply with the waste hierarchy [16] and would support demonstration of the use of Best Available Techniques (BAT).
- Restricted access decommissioning with robotic capability for high hazard environments such as high radiation, for example remote devices for small tasks and fully autonomous glove box operations.
- Assisted manual operations, using robotically enhanced operatives utilising wearable technology, robotic assistants to carry out the hazardous part of the task and technologies that can enable an operator to reach the work face quickly, for example robotic scaffolding.
- Reduction of deployment risk, using standardised equipment with a single set of spares that can be configured in a short space of time. The use of modular systems that can be adapted to suit on a task-by-task basis.
- Interim state enhancements using robotic techniques for autonomous management of facilities, that can maintain their own systems and manage nuclear waste without operator intervention over the lifetime of the stores.
- Increasing pond productivity, using techniques that can operate in low visibility to retrieve material from ponds such as heavy items, without disturbing visibility or residual sludge. This includes tetherless underwater systems inspection in areas that are difficult to access [17].
- Enabling technologies, to allow complete characterisation coverage of facilities, using the benefits of Virtual Reality (VR) to enhance operations and autonomous sampling."

Typical Challenges Associated with Robotic Deployment

Environmental conditions commonly encountered at Sellafield site are often referred to as the 'Four Ds' [18], i.e.: Dirty, Dark, Dangerous, and Dull (i.e., the latter referring to repetitive tasks). Common main constraints at Sellafield associated with robotic system deployments have been identified in the list below, which includes:

- Poor visibility.
- Unknown design and modifications.
- Condition/age of internals and externals.
- Degradation/decay/change of state of materials.
- Ergonomics/spatial arrangement of the environment.
- Dose levels/criticality/hydrogen generation.

Other common concerns about the application of robotic system deployments at Sellafield are captured in the list below, which includes:

- How to prevent injury to the operator?
- How to prevent damage to Structures, Systems, Components (SSCs) and other robotic equipment which might be deployed in the same environment?
- How to prevent dropped packages?
- How to prevent rogue operations?
- What is the most appropriate emergency stop mechanism?
- How to undertake recovery/maintain safe operations?
- How to provide cyber-secure robotic systems by design?

The challenge associated with robotic system deployment at Sellafield site is to ensure that the NDA and all UK nuclear facilities, can effectively exploit the technology to the full extent; in order to improve significantly the existing technical baseline for decommissioning the UK's civil nuclear legacy (e.g. safer, faster, cheaper and with less environmental impact).

Previous robotic deployments have been developed without site-wide co-ordination or standardisation; and consequently, Sellafield site uses a range of robots that run on different operating systems, in various programming languages. This has resulted in numerous bespoke operating platforms with associated costs and reductions in efficiency and flexibility.

In most other industries each robot works in isolation so that there is no need to standardise. A Game Changers innovation event was, therefore, organised by UK NNL in 2020 to try to resolve how different technologies can communicate with each other in one language.

Current robotic deployments at Sellafield site have so far been limited to lower levels of autonomy, gauged to be in the range of between 0 to 1 **(Figure 1)**. One of the main challenges to exploiting the potential offered by higher level autonomy is lack of stakeholder confidence in the reliability of robotic safety systems. This matter needs careful consideration in the promulgation of the Safety Case and is in part due to a historic lack of understanding and knowledge. It is argued that understanding the nature of the conditions and constraints faced at Sellafield will help to develop a range of possible future candidate safety measures for inclusion in a Hazard Management Strategy (HMS), which is proportional to hazard severity, enabling the risk to be reduced to ALARP.

Common Challenges Encountered in Robotic System Deployment

Innovation and the application of scientific discovery into useable technology involves the conversion

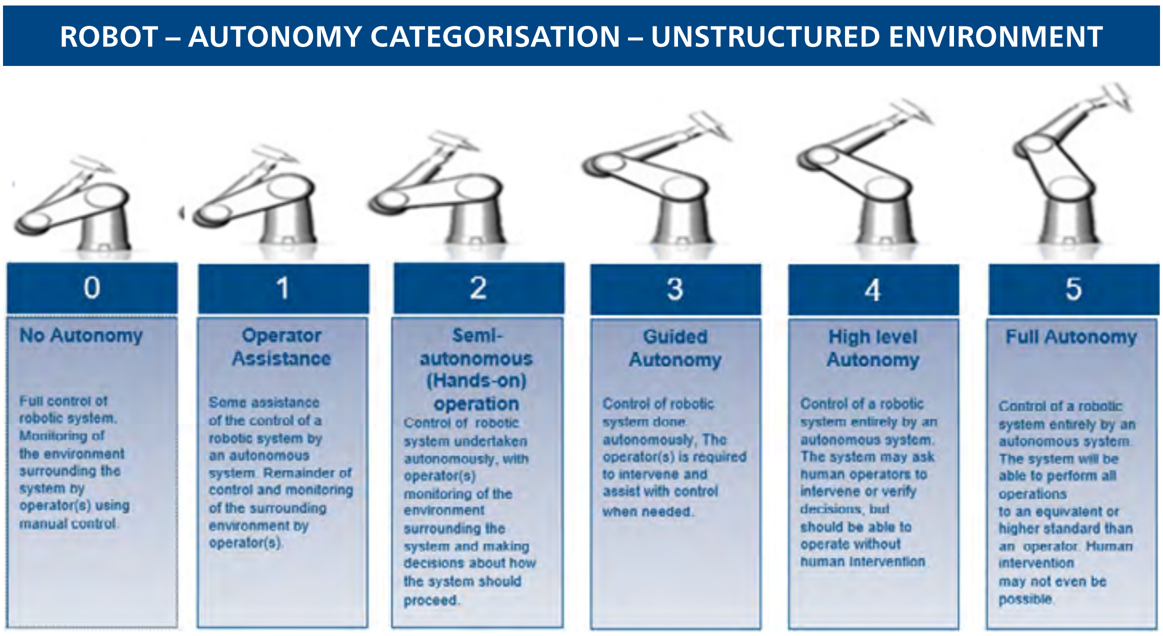

Fig. 1
Autonomous Robot System Levels.

or translation of science or an engineering solution to a problem. Mid-range TRL projects are by their very nature inherently higher risk projects as they are 'First of A Kind' (FOAK) and the route to the final solution cannot be determined accurately at project inception. Typical key risks include:

- Scope, programme, cost and performance uncertainties, which must be managed effectively;
- The ability to demonstrate the nuclear safety case becomes a requirement as technology develops;
- Trials and testing of equipment in support of verification and validation claims leading to UKCA marking;
- Potential commercial exposure requires that an appropriate commercial model be adopted from the start, particularly with respect to Intellectual Property (IP) management and partnership with other organisations; and
- There are reputational risks associated with these types of projects, given that they are often partially funded by UK Government investment vehicles.

Some of the typical challenges in technology development through to final UKCA marking and deployment are represented in **Figure 2** below.

Common challenges which can lead to delays in the development of a project, eventually resulting in a scenario where a project may require a break and a further procurement exercise to be undertaken, alongside consideration of cultural risks. Plant owners normally align their perspective with safety arguments and are risk averse. They do not like the idea of change, tending to favour how things have always been done. This can be paradoxical, as change is usually resisted even when there have been demonstrable advances in materials, technologies and processes developed to be safer and more efficient. This cultural default position can be characterised by the question: 'why change?'

Resistance from middle managers can be based also on a fear of non-compliance. However, Regulators are increasingly pushing for innovation and change, and senior managers aspire to 'succeed'. In reality operators do look for change, but it is down to those who sign off on the design and technology to be implemented. Arguably these are the 'gatekeepers' preventing innovation. For change in the prevailing culture to occur there is a need for a 'new generation mindset'. We can look to other highly regulated industries to see how technology, advancements, innovation and breaking the norm might be possible. The culture of an organisation can be understood as having three levels. The top level is defined as the tangible level, demonstrated through artifacts. The culture of the nuclear sector is characterised visibly through things such as its physical environment, nature of security, spoken and written language and observable behaviours. This is what most people are referring to when they talk about an organisation's culture. When change is discussed, this visible level is what is in people's minds. However, underpinning this visible level are two deeper, invisible levels: the values level and the basic assumptions level. Basic assumptions are completely invisible and are always very slow to change in any organisation or industry culture. Equally slow to change would be values. Values are observable through, for example, the way things are done, the way procedures and rules are prosecuted. Superficial changes at the level of artifacts will not have a significant and lasting impact, unless underpinned by changes in values [Reference 19]. Language and terminology, visible cultural characteristics, are key for successful integration. Arguably, it is important to be careful with language. Why use the word robot if the technology is actually an advancement or an upgrade?

Currently, physical mechanical hard stops are positioned to limit robot movement as a safety feature

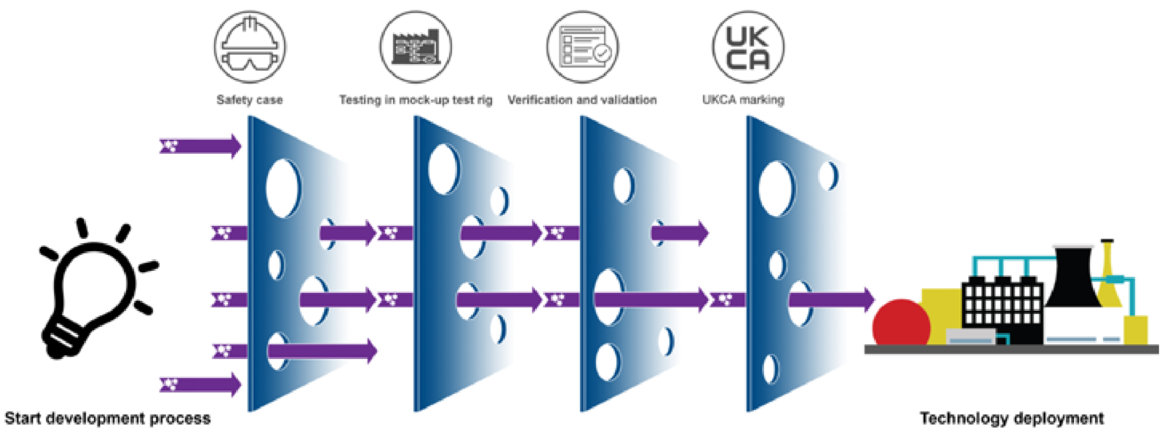

Fig. 2
Typical Challenges During Technology Development.

within the nuclear industry, whereas software interlocks could be employed instead, as in other sectors. This is as much a feature of nuclear industry culture as it is logic. The use of hard stops may be viewed within the culture of another industry sector as draconian. Arguably, software limits could be commonplace, allowing software to control robot movement effectively and safely. Safety cases would need to adopt new ways of thinking in order for robotic systems to be successful. Common issues and problems encountered in mid-TRL projects during delivery include:

- Project definition: requirements capture; front end loading (an important concept in the management of projects); insufficient scope definition; optimistic estimates of project costs and resources (the impact of optimism bias is an important concept that needs to be better understood).
- Resource management: strategic/tactical relationship in the context of organisational objectives and priorities. Behaviours tend to be defensive and therefore conservative and default to: no change, nothing new, cannot be done, cannot sign off, causing a slowing down; due to several iterations of meetings to 'kick the problem into another meeting'. This is rooted in the organisational culture. Resources are often not available, due to other work commitments and facilities may not be available also.
- Governance: lack of ownership, i.e. accountability; insufficient project governance; risk management failing to focus changes in a dynamic context and complex decision making process; inadequate change control, including changes to scope.
- Culture: risk aversion; reluctance to change – a mind-set rooted in the prevailing culture, perceiving change agents as disruptors (negative and dangerous) technologies can be perceived as 'too advanced' for implementation into 'our industry'.
- Nuclear industry culture is mentioned briefly above and is inextricably connected with organisational cultures within the sector. Risk and uncertainty are also central considerations. The management of risk lies essentially in the domain of programme and project management. Best practice, based on research, would suggest that the management of risk constitutes the major part of the practice of the management of projects [20].

Lessons Learned

From a review of the delivery of UK NNL's mid TRL projects, the following conclusions could be drawn. It would be helpful to reduce uncertainty from the decision-making process. This would be best achieved through the conversion of uncertainty to risk, which can then be treated and managed.

Collaboration on what have been identified as 'hot topics' may be a productive way of recognising how to strengthen collaboration. A method for achieving this would be to employ a Hazard and Operability Study (HAZOP) approach at an early stage, relevant in the context of front-end loading, in project management terms.

It is recognised that innovation is necessary in order to accelerate and make safer the new decommissioning baseline. New technologies, for example, the implementation of robotic solutions, could reduce human presence in hazardous environments, making processes safer and more efficient.

It is suggested that there are three different types of research-led organisation: internal, external and Small and Medium Enterprises (SMEs). These own the technologies and approaches used to solve challenges in the nuclear decommissioning environment; and translate new science and technologies into applications.

Ways need to be found to encourage a deeper understanding of the potential contribution of FOAK solutions, where no one simple solution currently exists. This involves fully understanding the value of creativity on developing solutions and the role that disruptive technologies, the norm in other industry sectors, can play.

It is argued, there is a need for a cultural change in the nuclear industry to enable innovation to occur more readily. It is suggested that internal and external research organisations need to be involved in the necessary cultural changes. Academia plays an important role in generating and translating IP at TRL 1-3 levels. Translating this into the next TRL 4, 5 and 6 requires cultural change, in order that approvals can be granted to enable prototypes to be tested and new ideas to be applied.

A good example of this is the problem of UKCA marking. For some, it is considered to be unrealistic that experimental robotic equipment developed at universities explicitly for the purposes of R&D or test deployments can be subject to UKCA marking in the way that industrial equipment is required to be, and indeed that the UKCA mark does not substitute for risk assessments.

However, this can be addressed by the acknowledgement that such a requirement before any commercial robotic purchase and/or full deployment is for a legitimate purpose in order to be fully legally compliant, and to facilitate approval for the technology to be deployed at a nuclear licensed site such as Sellafield. The only time UKCA marking is formally required is after R&D trials have been completed, and a project moves on to a stage requiring the purchase of a commercial technology product. To minimise such challenges, universities from when beginning to develop experimental robotic equipment should routinely look to keep a robust technical file, detailing all necessary advancements with the technology. In so doing, this technical file will make the expected eventual process step to apply for UKCA marking for the robotic equipment far easier and more likely to succeed, facilitating its advancement to full deployment.

The economic and logistical constraints, currently manifested in the nuclear sector as culturally based behaviours and processes, can sometimes slow innovation. Outside of legal compliance, cultural change in combination with recognised, reliable risk management can be a solution to this problem; but this requires a deeper understanding of the role played by regulation in relation to technological development and advances in science, in order to facilitate the valuable contribution that SMEs and other research organisations play in the translation of new scientific discoveries into industrial applications. As mentioned above, the language used and the way in which things are done in the nuclear context are both a manifestation of culture as well as symbolic and influential in maintaining that culture, to the extent that innovation can be slowed; whereas, in reality there are multiple routes which would achieve a given outcome [21].

Way Forward

Arguably an agenda could be developed within the nuclear decommissioning community that begins to address challenges to new ideas and innovations reaching decommissioning sites. Academic researchers, the ONR and Sellafield are interested in this problem and have identified that the main challenge occurs within the actual process of getting an idea to move forward.

What would really begin to unlock the resistance to change would be a robust model for a process, with supporting documentation, to form the basis of a viable way of progressing ideas from laboratory to site. This should involve connecting the process with the regulatory framework in a way that recognises the importance of timing. Often, ideas are turned off too soon. Introducing regulatory review at an appropriate point in time would go some way in preventing challenges to innovation. A documented process that supports this purpose is needed.

The 'game changers' are the SMEs and other research organisations, supported mainly by the National Nuclear User Facility (NNUF) and Innovate UK but, arguably, in the current risk averse climate these funding bodies are setting the game changers up for a fall.

The concept of developing a taxonomy idea and innovation types would be an effective and useful construct to assist the classification or categorisation of ideas and innovations at an early stage. A new process model for innovation and change would be able to relate to these different categories of idea/innovation, facilitating the tailoring of approaches to their rigorous consideration in a risk-based, meaningful way.

Mid-TRL projects are by their very nature inherently high risk projects. These are FOAK and their route to final solution cannot be accurately determined at project inception. Typical key risks need to consider the following: scope, programme and cost uncertainties, which must be managed effectively as technology develops. This requires the ability to demonstrate a nuclear safety case. Potential commercial exposure requires that an appropriate commercial model be adopted from the start, particularly with respect to IP management and in partnership with other organisations. Reputational risk, associated with these types of project, needs to be managed, given that they are often funded partially by government investment vehicles. Effective risk management is essential; best achieved through project management, control, and delivery strategies, implemented from the outset.

The arguments above point to the need to establish a new 'delivery framework' at the core of all project delivery based on a stage-gate process approach. This delivery framework would ensure that projects are 'set up to succeed' by providing clear guidance on the specific checks and balances that need to be actioned throughout the project lifecycle, and prior to commencement of work.

The risk profile of projects would be assessed at bid stage and the appropriate level of project management and governance implemented to match the project risk profile. Furthermore, project owners would be responsible for a number of key aspects as follows:

- The identification and availability of facilities, equipment and people during the front-end project evaluation stage, and identification of appropriate and adequate resources.

- The definition roles, responsibilities and accountabilities across the delivery team and identification of project 'risks' (technical and commercial).
- Confirmation of benefits and requirements, specific deliverables, programme of work, key milestones, challenges, risks and critical path activities; and
- The design of governance, reporting, and communication strategies, to include progress, cost and risk.

The approach would ensure an appropriate management and governance structure, reporting and communications plans, and stakeholder management strategy. The transparency encouraged through this approach would result in strong engagement by the Regulator and key stakeholders; helping to stimulate a cultural change in the nuclear industry and support the development of robotic systems in nuclear decommissioning projects.

Acknowledgement

The authors would like to acknowledge funding provided towards developing this paper from the UK NNL Science & Technology Programme.

References

[1] Smith, R.; Cucco, E.; Fairbairn, C. Robotic Development for the Nuclear Environment: Challenges and Strategy. Robotics 2020, 9, 94. https://doi.org/10.3390/robotics9040094

[2] NASA, Technology Readiness Level, Available at: https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

[3] National Nuclear Laboratory "A Pragmatic Approach to Chemotoxic Safety in the Nuclear Industry", H Chapman, Marc Thomas, Stephen Lawton, ATW-International Journal for Nuclear Power, Issue 8/9/2019. Available at: https://www.yumpu.com/en/document/read/62806321/atw-international-journal-for-nuclear-power-08-092019

[4] Nuclear Regulation and Regulators Available at: https://tinyurl.com/967cabj5

[5] UK Government, Health and Safety at Work etc. Act 1974

[6] UK Government, Energy Act 2016

[7] UK Government, Nuclear Installations Act 2016

[8] Risk management: Expert guidance - ALARP at a glance: https://www.hse.gov.uk/enforce/expert/alarpglance.htm

[9] ONR Safety Assessment Principles 2014 Edition, Revision 1, January 2020

[10] https://www.pilz.com › TechBo_Pilz_safety_compendium_1004669-EN-01, 5th Edition March 2018

[11] Supply of Machinery (Safety) Regulations 2008, Version 2, November 2021

[12] European Parliament and Council of the European Union Machinery Directive 2006/42/EC

[13] NDA, Robotics and Artificial Intelligence Research and Development Preferred Option (Gate B) – Issue 1 March 2018

[14] Nuclear Decommissioning Authority Sets Out Its Grand Challenges, Available at: https://www.gov.uk/government/news/nda-sets-out-its-grand-challenges

[15] Sellafield Limited Medium to Long Term Research Needs – Supporting the Mission at Sellafield, Available at: https://tinyurl.com/y7nh98f9

[16] UK Radioactive Waste Inventory, Available at: https://ukinventory.nda.gov.uk/about-radioactive-waste/what-is-the-waste-hierarchy/

[17] Remotely Operated Vehicles James Fischer Nuclear, Available at: https://www.jfnl.co.uk/products/rov-systems/unmanned-aerial-vehicles/

[18] National Nuclear Laboratory and Sellafield Ltd (2020) Solving Sellafield's 4 Ds problem, American Nuclear Society, November 6, 2020. Available at: https://www.ans.org/news/article-2351/solving-sellafields-4-ds-problem/

[19] Schein, E. (2017) Organisational Culture and Leadership, 5th Edition, Hoboken, Wiley.

[20] Morris, P. (2013) Reconstructing Project Management, Chichester, Wiley-Blackwell.

[21] Von Bertalanffy, L. (1968) General Systems Theory: Foundations, Development, Applications, New York: George Braziller.

Authors

Howard Chapman
National Nuclear Laboratory
howard.chapman@uknnl.com

Howard Chapman is a Principal Safety Consultant and has worked in the nuclear industry for over thirty-five years, with vast experience in the production and management of radiological and high hazard chemotoxic safety cases at a number of sites throughout the UK and internationally. His career spans across all aspects of the nuclear project lifecycle. Howard led the safety case for the LaserSnake project which built a semi-autonomous robot controlled laser cutting capability in a cave environment within an active facility. Howard has also recently worked on a robotic safety project to meet the challenge for the adoption of a higher degree of Human Robot Collaboration at Sellafield site. This work has helped to develop a better understanding of generic robotic safety case considerations and the reliability of SMART protective measures available from current and emergent technologies across all key industrial sectors.

John-Patrick Richardson
National Nuclear Laboratory
john-patrick.richardson@uknnl.com

As Robotics Development Lead for the UK National Nuclear Laboratory, John-Patrick Richardson has responsibility for the development & technical delivery of NNL's strategy for the Robotics Capability through the co-ordination of customers, suppliers, universities and other companies. His responsibilities cover two main areas: leading on the development of the Robotics & Artificial Intelligence (RAI) Strategy for NNL and business development; and ensuring the technical delivery of RAI work across NNL.

Colin Fairbairn
National Nuclear Laboratory Limited
colin.fairbairn@uknnl.com

Colin Fairbairn is a Chartered Senior Mechanical Engineering Technologist as part of the National Nuclear Laboratory's Remote Engineering, Design and Robotics team; and NNL Technical Lead, specialised in robotics and artificial intelligence and remote engineering. An advocate for robotics and smart technology, Colin develops innovative robotic solutions for remote deployment in hazardous radioactive environments. Colin is responsible for leading the technical delivery of NNL robotics projects, translating novel technology for the use in nuclear decommissioning.

Antonio Di Buono
National Nuclear Laboratory Limited
antonio.dibuono@uknnl.com

Antonio Di Buono is a Research Technologist in the Instrumentation and In-situ Analysis team. He is working on several aspects of instrumentation development, focusing on wireless communications for nuclear decommissioning environments and the use of digital technologies. Antonio joined NNL after completing his PhD project at the Centre for Innovative Nuclear Decommissioning (CINDe) in 2020. His research involves the design, prototyping and experimental evaluation of wireless sensing systems to support decommissioning activities and to provide remote sensing capability in nuclear material storage facilities.

Andrew Gale

Co-Author Professor Andrew Gale is an emeritus Professor of Project Management at the University of Cumbria.