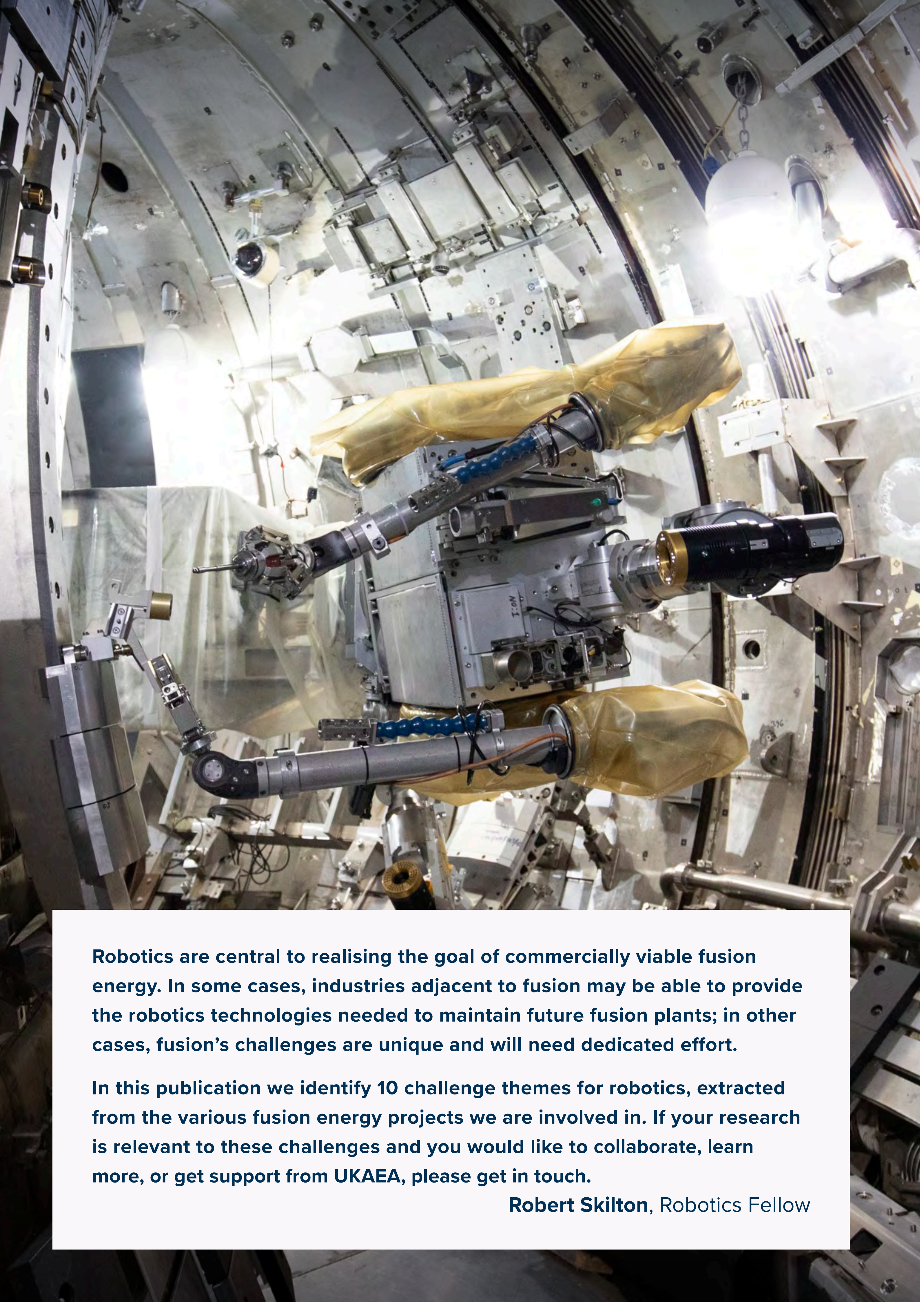
UK Atomic Energy Authority

Robotics challenges for fusion energy

3rd edition 2024



Robotics are central to realising the goal of commercially viable fusion energy. In some cases, industries adjacent to fusion may be able to provide the robotics technologies needed to maintain future fusion plants; in other cases, fusion's challenges are unique and will need dedicated effort.

In this publication we identify 10 challenge themes for robotics, extracted from the various fusion energy projects we are involved in. If your research is relevant to these challenges and you would like to collaborate, learn more, or get support from UKAEA, please get in touch.

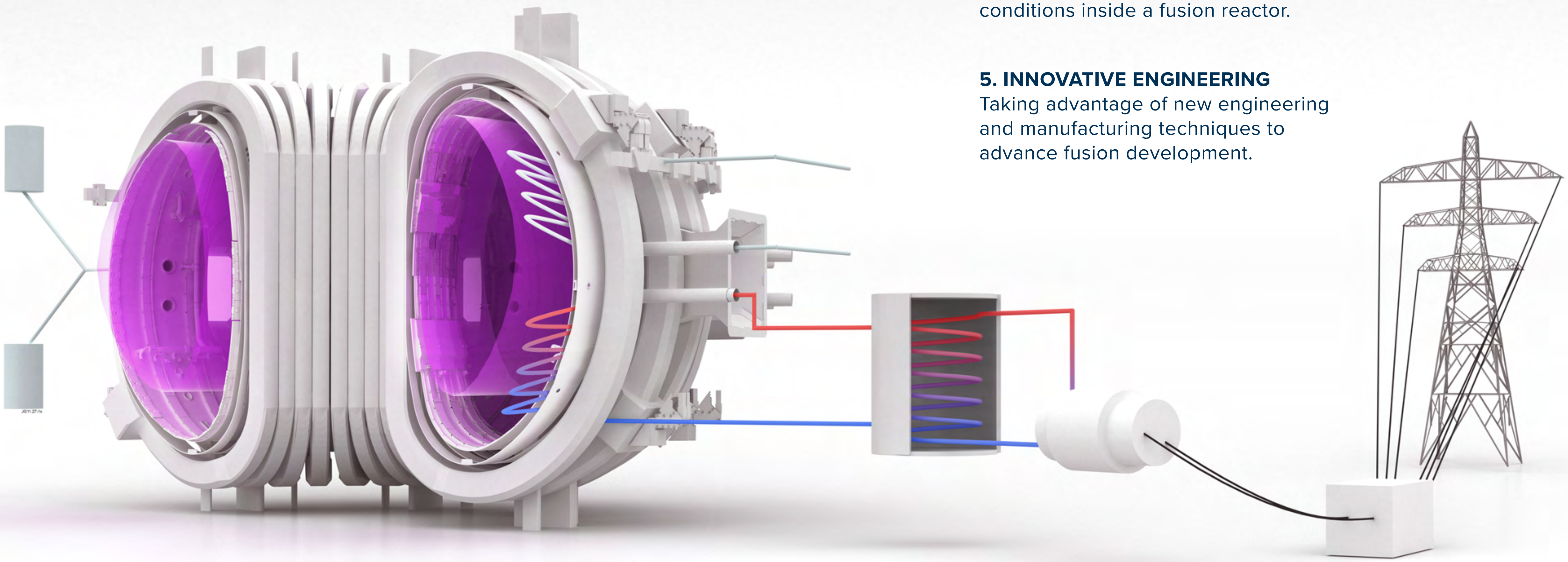
Robert Skilton, Robotics Fellow

CONTENTS

Fusion Energy

Fusion energy research themes

1. PLASMA SCIENCE
Confining fusion fuel in a plasma at temperatures 10 times hotter than the sun's core.



2. FUEL HANDLING
Breeding and handling tritium fuel to power commercial fusion reactors.

3. PLASMA EXHAUST
Designing an exhaust system to divert heat from the plasma.

The UK Atomic Energy Authority (UKAEA) is turning the process that powers the sun into carbon-free, safe and abundant electricity for a cleaner planet.

More than 80% of the world's energy still comes from fossil fuels. Climate change and diminishing fuel reserves mean the race is on to find alternative, sustainable technologies to supply a growing global population. With no greenhouse gas emissions, inherent safety features and virtually limitless fuels, fusion has a key role to play in the energy market of the future.

Fusion is moving from the research phase to the delivery phase. ITER, the first industrial-scale fusion device, is under construction, and prototype power stations are already being designed around the world.

However, in order to realise fusion's potential as a source of efficient, cost-effective and reliable energy we will have to solve a series of complex science and engineering challenges.

UKAEA has identified that robotics-based maintenance is one of six essential challenges it must address.

4. MATERIALS SCIENCE
Developing materials that can withstand the demanding conditions inside a fusion reactor.

5. INNOVATIVE ENGINEERING
Taking advantage of new engineering and manufacturing techniques to advance fusion development.

6. ROBOTIC MAINTENANCE
Maintaining the reactor entirely with robotics and remote maintenance techniques.

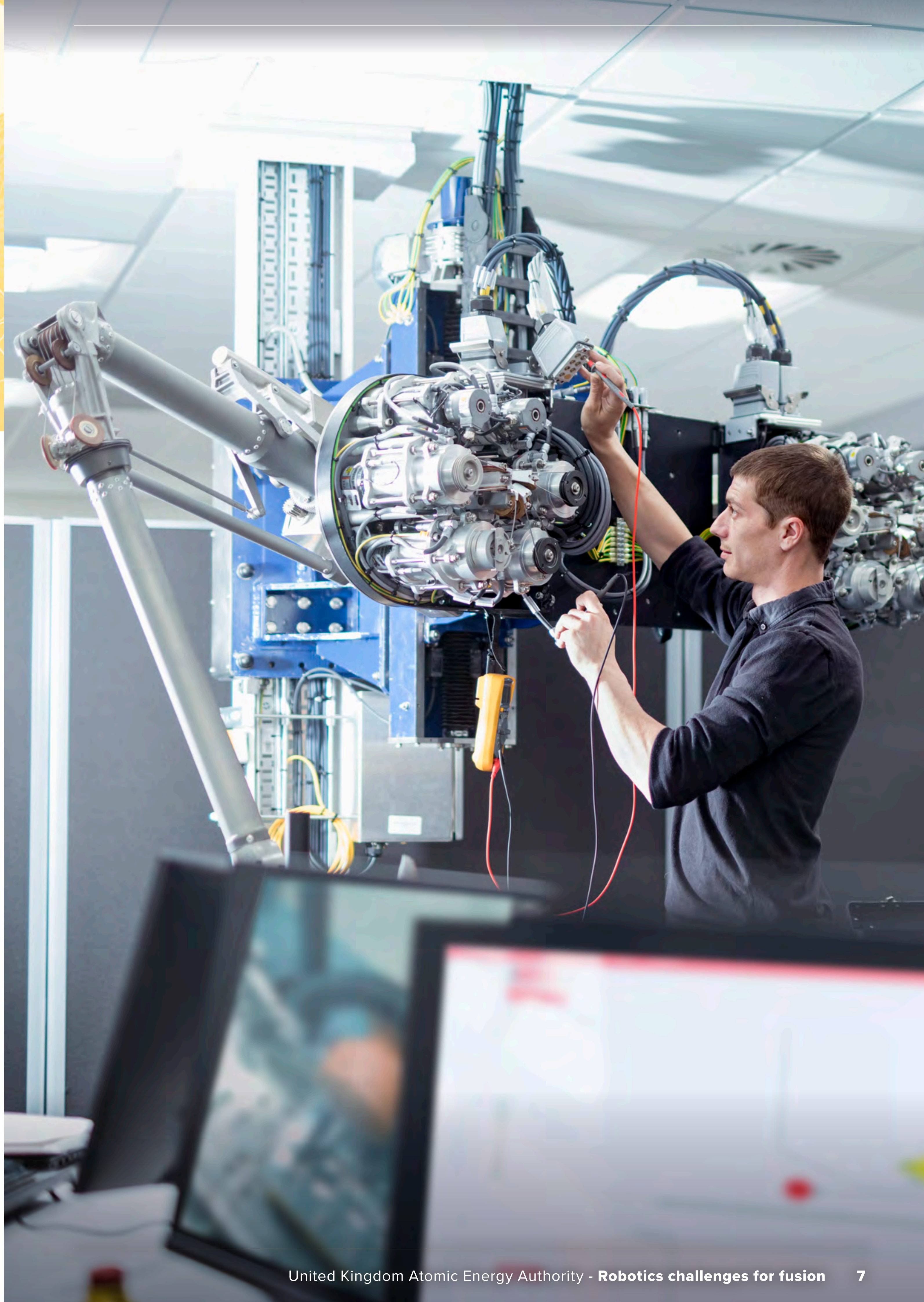
Mission and Goals

UKAEA's mission is to lead the delivery of sustainable fusion energy and maximise the scientific and economic benefit.

UKAEA researches fusion energy and related technologies, with the aim of positioning the UK as a leader in sustainable energy.

The **five interconnected strategic goals** to deliver on this mission are:

- Solve challenges of sustainable fusion energy - from design through to decommissioning - with world-leading science and engineering.
- Enable partners to design, deliver, and operate commercial fusion power plants.
- Drive UK economic growth and a thriving industry that exports fusion technology around the world.
- Create clusters that accelerate innovation in fusion and related technologies.
- Develop the talented, diverse people needed to deliver fusion energy.



Remote Applications in Challenging Environments

RACE is the UKAEA's centre for Remote Applications in Challenging Environments.

Robotics and remotely operated tools are a fundamental part of operating fusion power plants.

The requirement to maintain fusion devices remotely is now considered to be device-defining – meaning the architecture of a fusion power plant must be designed to be inspected, maintained, and upgraded remotely using robots. It is also mission-critical because reliable, fast intervention is necessary to maximise plant availability and hence achieve commercial viability.

RACE is a world-leading centre for robotics in fusion. It brings together the technology and expertise to develop the robotics and people who will deliver commercially viable fusion and, through its collaborative approach, is enabling an innovation pipeline of UK and international organisations which can serve the fusion mission.

RACE is therefore central to delivering the UKAEA's mission.

RACE is more than fusion: the skills and talent it develops have an impact on the UKAEA's goals beyond fusion by contributing to UK economic growth and technical capability. RACE creates impact and benefits from partnerships in other sectors with challenging environments, for example space and nuclear decommissioning.

RACE operates across the full lifecycle of remote maintenance systems and associated technologies, from pre-concept through to decommissioning.

RACE collaborates with others to develop the capability needed for fusion:

- Develops capability in remote operations and associated technologies
- Delivers capability to programmes and facilities internationally
- Transfers capability to others through training and partnership

How we operate

We collaborate on research to align with expertise, understand use cases, and maximise real-world impact

We host and provide test facilities and hardware platforms to facilitate cost-effective research

We make fusion challenges accessible to leading researchers by facilitating easy access to knowledge and facilities

We align our programme with wider needs outside of fusion to maximise mutual benefits, engage broader expertise, and leverage available funding

We act as a hub to connect end users, researchers, suppliers, and funders for mutual benefit

We form a ‘Viable Innovation Pipeline’ for organisations who understand our problems and can provide solutions

We work proactively to remove barriers to progress and engagement

RACE Research Team

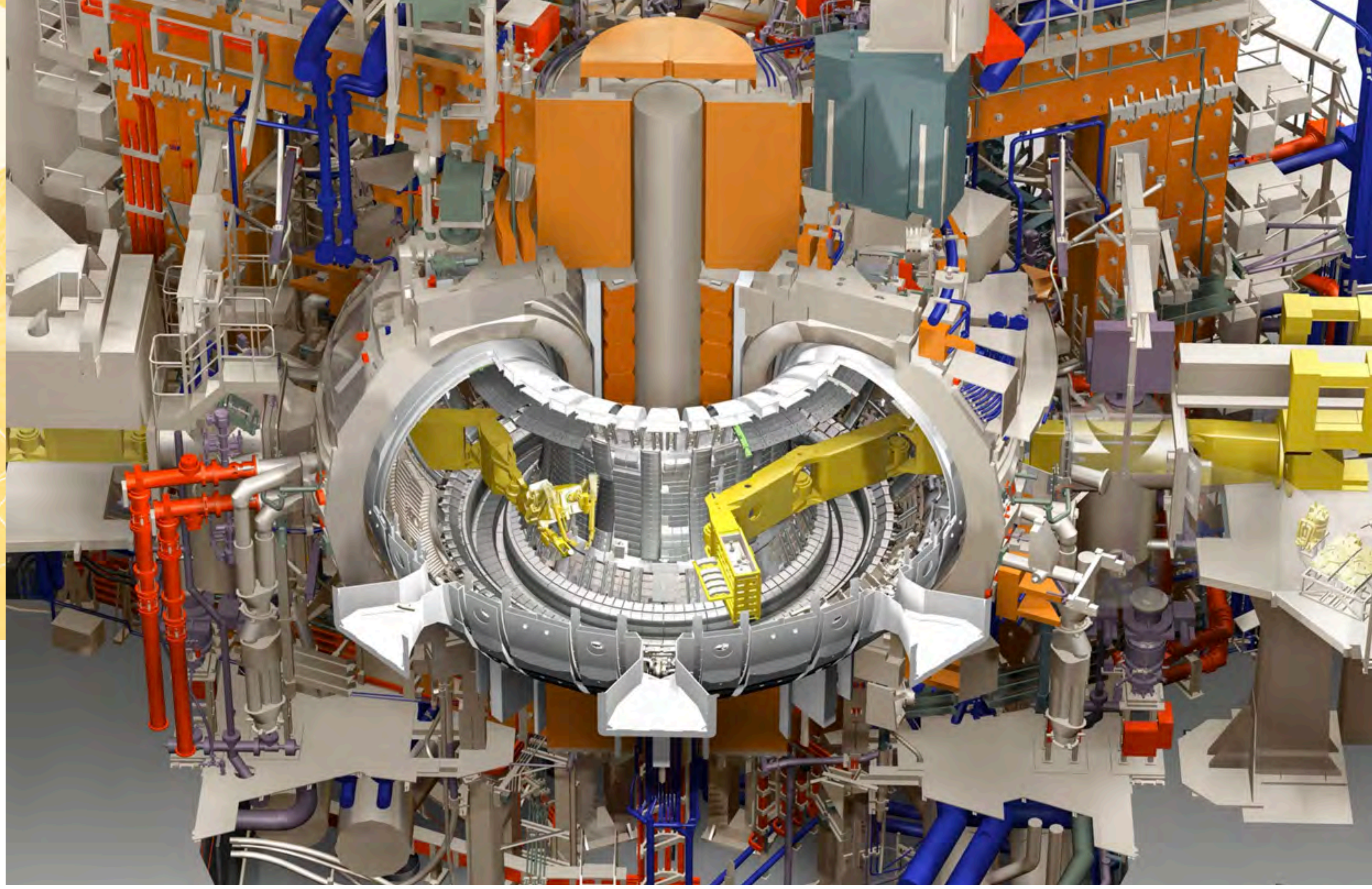
RACE has two core teams: a Research Team focused on early-stage technology development (TRL 2-5) and an Engineering Team focused on delivering that technology (TRL 4-8).

The RACE Research Team is focussed on the future, with a 5-15 year forward view. It engages the required research and academic collaborations to achieve UKAEA's robotics mission. Its role is to develop new knowledge and capability that supports delivery in the medium- to long-term, and bring together new technologies from universities and other industries to meet the RACE challenges.

The RACE Research Team has two primary goals:

1. To attract and enable the world's leading researchers across a wide range of fields to work on the UKAEA mission of enabling fusion through robotics and maintenance.
2. To reduce and remove barriers to technology and capability in other areas relevant to fusion.

The Research Team works closely with the Engineering teams to understand the real-world challenges and constraints inherent in the development of fusion energy plants. They work to translate scientific developments, research progress and emerging technology areas to impact the development of new reactors. They act as an "intelligent customer" for research output, and maintain awareness of a wide range of emerging technologies and fields of research.



In developing systems for challenging environments, RACE takes a holistic approach to the systems it develops. Building robotics for these environments needs support from many other areas of engineering:

- Materials that can withstand the extremes and still function within an electromechanical system in well-defined ways
- Cutting and joining technologies that robots can carry out autonomously at a distance with complete safety
- Structural engineering to support and autonomously move heavy loads with high accuracy
- Control systems that can coordinate the actions of multiple devices to achieve complex maintenance tasks
- Adaptive systems and AI decision tools trustworthy enough to be used to plan and optimise when and how tasks are carried out
- User interfaces that keep operators informed and in control without being overloaded

These diverse areas of engineering must be integrated into systems that will need to last the decades-long lifetimes of the reactors they maintain, and in some cases they cannot be removed once they are installed.

Global RACE

RACE is part of a global effort to create sustainable fusion power and is directly involved in both the UK and European efforts to build sustainable fusion reactors.

JET is the UK-based European experimental fusion device. After reaching a significant milestone in 2022, producing a record-breaking 59 megajoules of sustained fusion energy, RACE is looking ahead to the decommissioning phase.

ITER is under construction in Cadarache in the south of France, and is the most advanced fusion project. ITER is expected to reach its first deuterium-tritium operations in 2035.

STEP is the UK's fusion prototype power plant. It will include much of the infrastructure and facilities seen on any operational power station. Completion of construction is targeted for around 2040.

DEMO is the planned European successor to ITER, and aims to produce 500 MW of electrical power to the grid, a similar level of output to a standard electrical power plant. DEMO and should be online in the middle of the century.

RACE is involved in providing robotics-based remote maintenance in these projects, each of which requires robotics for long-term maintenance. RACE collaborates globally to develop the robotics to meet the engineering and scientific challenges of these vital projects.

ITER

ITER is the next generation fusion research device being built in the south of France that will achieve 'a burning plasma'. This is one of the required steps on the way to commercial fusion power.

Remote Handling (RH) has an essential role to play in the ITER tokamak. Once fusion begins, changes, inspections and repair of the machine components in activated areas will only be possible using remote handling techniques. Through the ITER Robotics Test Facility hosted at RACE is working with ITER to develop RH equipment and processes. Under this programme we demonstrate the feasibility of remote maintenance activities at ITER. RACE is also supporting industry in delivering dedicated RH systems. This is helping to derisk complex, first-of-a-kind designs and operations.

ITER provides some seriously challenging environments for robotics: high radiation doses elevated temperatures; limited access; large reactor components; and some very challenging inspection and maintenance procedures to implement quickly and

STEP

STEP is a UKAEA programme that will demonstrate the ability to generate net electricity from fusion. Key challenges for the STEP programme include determining how the plant will be maintained through its operational life and proving the potential for the plant to produce its own fuel.

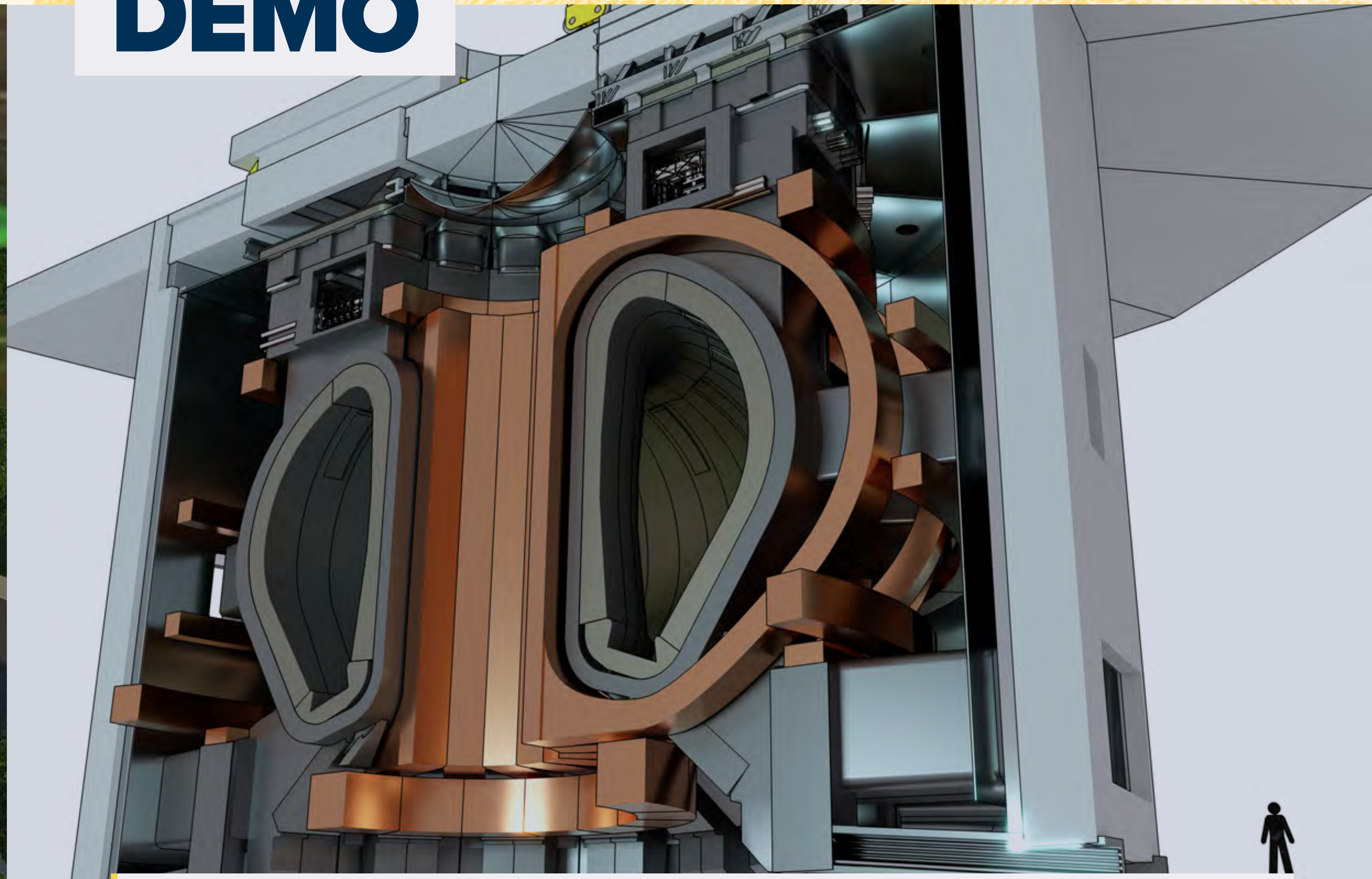
RACE leads the development of remote maintenance processes and technologies, from in- and ex-vessel maintenance through to decontamination, storage and disposal of activated components. RACE's remote maintenance engineers are integrated in the STEP team and are bringing their knowledge to the design of components for remote maintainability.

RACE has a key set of capabilities which will be required by STEP to meet the demands of an acceptable through-life affordability, both in construction, operation – including maintenance and waste handling – as well as onward decommissioning. Indeed, the through-life cost is one of the critical KPIs which will be monitored in the overall business case.

The objective is to produce a feasible scheme for the maintenance of the STEP Prototype Reactor (SPR) at a conceptual level that demonstrates, with feasible technology development, that the critical and vulnerable components can be replaced.

This work provides the STEP programme with confidence that the proposed reactor's operation, control and maintenance strategy is safe, affordable, available, and technically credible.

DEMO



DEMO (or EU-DEMO) is the European successor to ITER – a proposed grid-connected fusion device that will demonstrate safe and consistent generation of electricity.

RACE is the lead laboratory for EU-DEMO's Remote Maintenance Work Package. It is responsible for leading the development of remote maintenance technologies, and integrating enabling technologies developed across the EU and the UK.

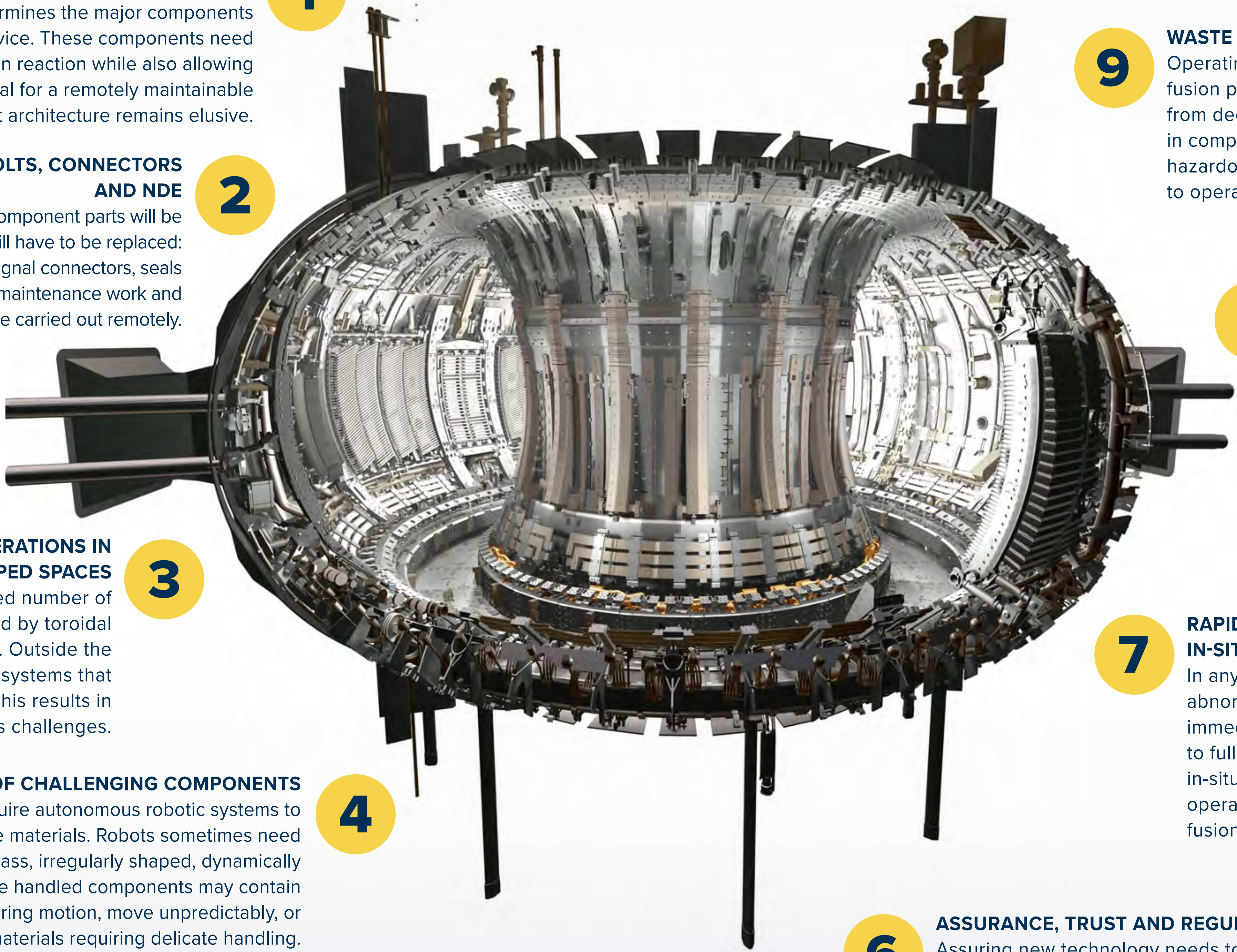
Minimising plant downtime and maximising availability will reduce the cost of electricity. An effective remote maintenance strategy for DEMO is crucial for the commercialisation of fusion energy. Remote maintenance is 'device-defining', driving the design of the plant architecture.

Where the remote maintenance strategy requires novel solutions, RACE leads the development of the technologies to meet the challenges.

Top 10 challenges

RACE has identified ten key challenges for fusion remote maintenance:

Key challenges for robotics in fusion & beyond



1 ARCHITECTURE OPTIMISATION INCLUDING DESIGN FOR REMOTE MAINTENANCE
The physics of fusion reactions determines the major components needed to realise a working fusion device. These components need to have properties that enable the fusion reaction while also allowing them to be maintained. A viable proposal for a remotely maintainable fusion powerplant architecture remains elusive.

2 SERVICE JOINING INCLUDING PIPES, BOLTS, CONNECTORS AND NDE
Over the lifetime of a reactor many component parts will be degraded by the extreme environment and will have to be replaced: pipes, flange bolts, electrical connections, signal connectors, seals and more. Once fusion is started this regular maintenance work and in-situ repair will have to be carried out remotely.

3 SLENDER MECHANISMS AND OPERATIONS IN CONFINED, CRAMPED SPACES
Access into the fusion vessel is via a limited number of access ports with dimensions constrained by toroidal field magnets and other critical structures. Outside the vessel, in close proximity, are support systems that access the chamber through the ports. This results in significant access challenges.

4 HANDLING OF CHALLENGING COMPONENTS
Remote maintenance tasks often require autonomous robotic systems to handle components, tools, and waste materials. Robots sometimes need to manage components that are high mass, irregularly shaped, dynamically unstable, or have unknown properties. Some handled components may contain liquids that shift their centre of gravity during motion, move unpredictably, or involve fragile waste materials requiring delicate handling.

5 ENVIRONMENTAL COMPATIBILITY INCLUDING RADIATION, VACUUM, MAGNETIC FIELDS
The operating environment in which robots must carry out maintenance and inspection tasks is extreme, with activated components, residual magnetic fields and high ambient temperatures. These extremes pose significant challenges to the design of remote maintenance systems.

6 ASSURANCE, TRUST AND REGULATION
Assuring new technology needs to start with the technology development process itself. Providing assurable, trustworthy and deployable physical and digital systems is essential to carrying out the complex tasks needed for fusion remote maintenance. They must be trustworthy even after decades of operation.

7 RAPID RESPONSE INCLUDING INSPECTION AND IN-SITU REPAIR
In any complex system there will be operational abnormalities. In some cases there will be a need for immediate intervention without the opportunity to transition to full shutdown. Technology for rapid intervention and in-situ repair must operate quickly to minimise downtime, operating through vacuum barriers and in the most extreme fusion environments.

8 MAINTENANCE PRODUCTIVITY
Future fusion power plants will need to be productive enough to ensure sufficient return on investment by providing reliable, sustained electricity generation. This in turn relies on the high availability of the reactor and its support systems.

9 WASTE MANAGEMENT
Operating a fusion plant creates waste as products of the fusion process, from parts being taken out of service, and from decontamination. Disposal must be done safely and in compliance with regulations around the management of hazardous materials. Effective waste management is critical to operational efficiency.

10 THROUGH-LIFE COST REDUCTION FOR LONG-LIVED FACILITIES
Lifetime cost is a critical factor in the success of fusion-based electricity generation. Over its lifetime, a fusion plant will have a high potential for loss of efficiency that could drive up operating costs. Teams and systems should be able to adapt in a cost-effective way, to respond to changes in requirements and technologies.

Challenge 1:

Identification of fusion reactor architectures for remote maintenance

The physics of fusion reactions determine the major components needed to realise a working reactor. These components need to have sizes, positions and shapes that both enable reactor performance and allow them to be maintained.

Identification of maintainable reactor architectures involves a complex set of trade-offs between competing design needs. The consequence of failing to fully consider lifetime maintenance at the design stage will result in an unworkable reactor. A viable proposal for a remotely maintainable fusion powerplant architecture that balances these needs remains elusive.

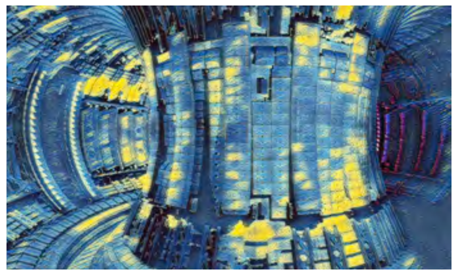
Design and development processes need to be established that enable remote maintainability to be integrated as a core requirement.

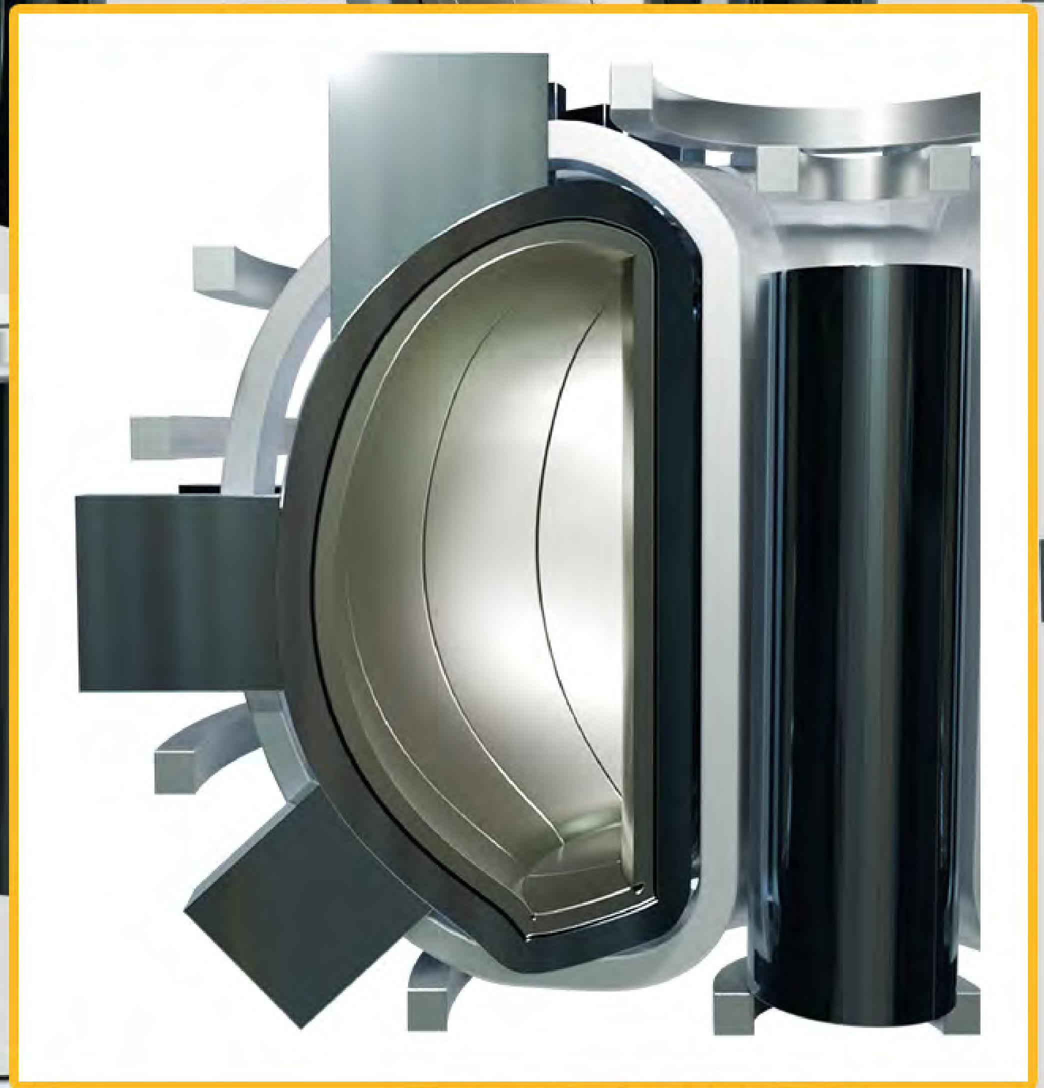
Critical topics

1. How to directly integrate the design of remote maintenance equipment into fusion reactor architecture designs to fully assure remote maintainability.
2. How to develop methods to establish and communicate the principles of design for remote maintainability.
3. How to drive convergence on maintainable reactor architectures.

Example research areas

- Methods for automated parametric design of robotic systems
- Architectural frameworks to promote operational agility
- Hardware interfaces to promote ease of remote operation
- Service connections designed for remote operation
- AI-driven automated architecture development





Challenge 2:

Service joining including pipes, bolts, connectors and NDE

Over the lifetime of a reactor, many component parts that make up its support systems will be degraded by the extreme environment and will have to be replaced. Once fusion operations begin, regular maintenance work and in-situ repair will have to be carried out remotely. This involves disconnecting and reconnecting pipes, flange bolts, electrical connections, signal connectors, seals and more.

Service systems involving removal and reconnection must continue to maintain regulatory compliance and each task outcome must be validated before operation can recommence. For example, pipes that are reconnected by welding will need to have the welds remotely validated, often where access is only possible from one side of the pipe wall. Developing technology that can meet these space, time and quality constraints is a core challenge.

Critical topics

1. How to cut, weld, connect and disconnect services.
2. How to validate this work.
3. How to assess the condition of parts.
4. How to carry out these operations with systems operating at a distance in a fusion environment.
5. How contamination and waste generated can be minimised to a level that will not compromise future operation.

Example research areas

- Remote pipe cutting and preparation for welding
- Novel methods for pipe joining
- In-situ weld repair techniques
- Radiation-compatible non-destructive examination methods
- Swarf and waste control technologies
- Computational weld modelling

Challenge 3:

Slender mechanisms and operations in confined, cramped spaces

Many fusion systems that will require maintenance will be tightly packed together, resulting in significant access challenges for robotics.

Access to the inside of the fusion chamber is via a limited number of access ports, with dimensions constrained by toroidal field magnets and other critical structures. Maintaining, inspecting or replacing in-vessel components involves reaching through these narrow, congested ports. This has historically led to designs involving long and slender robotic boom systems, which create constraints on strength and payload while exhibiting issues around vibration and flexible deformation. This in turn imposes constraints on the actuation and sensing systems needed to operate.

Outside the vessel, packed in close proximity, are support systems: heating, diagnostic, magnet and driver systems, cryogenic systems, pipes and cooling systems, fuel injectors, electrical power and support structures. Maintenance and inspection of these systems is made more challenging by proximity to a range of radiological and chemical hazards. This, combined with the limited access and confined spaces, mean that direct human maintenance is often impossible.

Critical topics

1. How to design and build a range of long slender robotic systems that can operate at a distance in extreme environments, and that can handle a wide variety of payloads.
2. How to control these systems to carry out complex functions over long periods of time with very high levels of reliability.
3. How these systems can adapt as their working environment changes over time.
4. How to plan and execute routine and unexpected maintenance missions.

Example research areas

- Modelling and system identification for control applications
- Control strategies for reducing flex and vibrations in long manipulators
- Mechanical damping systems for boom arms
- Novel methods for automated design of long-reach arms
- Planning algorithms that account for highly confined spaces
- Human interface enhancements for collision prevention

Challenge 4:

Handling challenging components

In fusion environments robots sometimes need to handle payloads that are irregularly shaped, dynamically unstable, or have unknown properties. This may include components, tools and waste materials.

High-mass payloads are particularly challenging, especially when they approach the robot's maximum capacity and need to be manoeuvred in confined spaces. Some handled components, like large sections of the reactor's inner 'blanket' wall, may contain liquids that shift their centre of gravity during motion, move unpredictably or involve fragile waste materials requiring delicate handling. Even regular maintenance tasks, such as the handling of electrical cables, a welding torch or a valve, can present significant manipulation challenges.

In each area of maintenance different operating scenarios need to be carefully considered, including the possibility that remote maintenance may be needed where it was not originally intended or designed for. For example, there may be cases where human intervention was assumed to be feasible but is no longer possible.

New technology may also provide opportunities to perform remote handling tasks that are not currently possible.

Critical topics

1. How robots can be built to autonomously handle complex objects and tools, and do so with very high levels of reliability and trust.
2. How to design handling systems that can deliver dexterity while keeping the forces and moments imparted under control.

Example research areas

- Dynamic modelling techniques for understanding the behaviour of challenging payloads
- Safe, autonomous handling of arbitrarily shaped payloads with challenging dynamic properties
- Visual methods for grasp detection in challenging environments
- Methods for enhancing human teleoperated handling
- Learning-based methods for handling delicate objects and cables, brushing, swabbing, and wiping

Challenge 5:

Environmental compatibility including radiation, vacuum, and magnetic fields

The environment in a fusion device is extreme, including neutron fluences, high levels of gamma radiation, powerful magnetic fields, vacuum pressures, high temperatures and thermal cycles.

Robots carrying out remote maintenance must be able to operate with activated components, residual magnetic fields and high ambient temperatures. These conditions are exacerbated when rapid inspection or repair is needed to resolve unexpected issues through direct intervention, with no time to wait for the environment to settle.

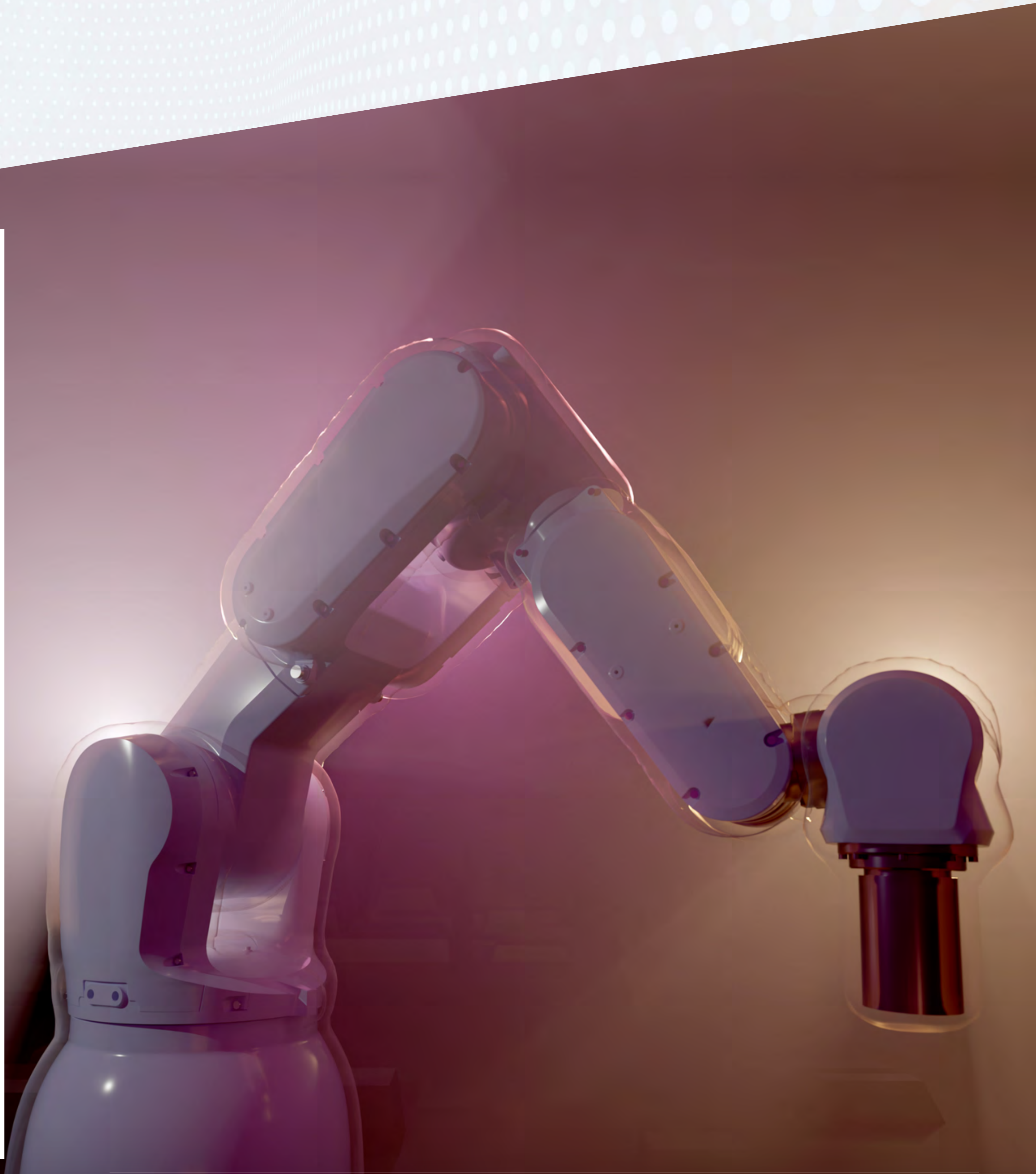
Gamma radiation poses particular challenges for the multiple electronic systems that robots rely on: sensors (cameras, LIDAR, etc), motor drivers, and the provision of computational power needed to control and automate tasks. Even outside the vacuum vessel environment, robots will encounter a wide range of hazardous conditions when working in proximity to chemical and radiation hazards, or within hot cell maintenance areas.

Critical topics

1. Which materials can withstand the extreme conditions found in fusion devices.
2. How to make robot systems from appropriate materials.
3. How sensors can continue to operate in-vessel.
4. How actuators and robot systems should be designed for these extreme environments.

Example research areas

- Highly radiation-hard sensors and electronics able to withstand >1 MGy total gamma dose
- Radiation-hard communications interfaces and microprocessors
- Alternative semiconductor technologies such as silicon carbide, gallium nitride, diamond, etc
- Vacuum-compatible robotics
- Magnetic-field-compatible servomotors and motor drivers
- Use of optical fibres for sensing and communication
- Strategies for leveraging the effects of magnetic fields and radiation to achieve useful functionality (e.g. gamma voltaics)



Challenge 6:

Assurance, trust, and regulation

Providing assurable, trustworthy and deployable physical and digital systems is essential to carrying out the complex tasks needed for fusion remote maintenance. This trustworthiness must be maintained throughout decades of operation.

Assuring new technology needs to start with the technology development process itself. Safety in challenging environments is often achieved by utilising simple and proven components, to reduce complexity. However, this approach limits what can be accomplished, increasing time and cost. Excluding complexity is not compatible with the operational demands of a fusion plant.

Robot systems addressing tasks of greater complexity, especially where they must replace human decision making, demand a high level of trust in their ability to perform reliably and make high-quality decisions. This is particularly important when leveraging modern techniques such as machine learning to increase autonomy.

From rapid entry into hazardous areas through to repetitive inspection and dextrous handling tasks, designers, developers and regulators must all be aligned to achieve an optimal regulatory framework. Design and development processes must deliver the assurance that future systems are reliable, available, maintainable and safe.

Critical topics

1. How to assure and verify complex systems.
2. How to understand and influence the needs and constraints of future operators, and how to build and deploy human-compatible systems.
3. How, by design, to fully integrate safety, security and asset protection into a repeatable product lifecycle.
4. How to work with regulators on developing appropriate assurance.

Example research areas

- Explorations of the full potential when using regulatory sandboxes in complex hazardous environments
- Assessment of human factors surrounding interaction with complex physical systems
- Design, assurance and validation methods needed to progress autonomous decision making from advisory systems through supervisory systems and onward to fuller autonomy

Challenge 7:

Rapid response, including inspection and in-situ repair

In any complex system there will be operational abnormalities. These abnormal events will be picked up through long-term and short-term monitoring, and by periodic inspections most often conducted remotely.

Critical decisions will need to be made about performing rapid intervention without a transition to full plant shutdown. For example, it may be possible to operate without discharging superconducting magnets, restoring ambient atmosphere, allowing thermal and radiological conditions to reduce, or removing equipment obstructing port access.

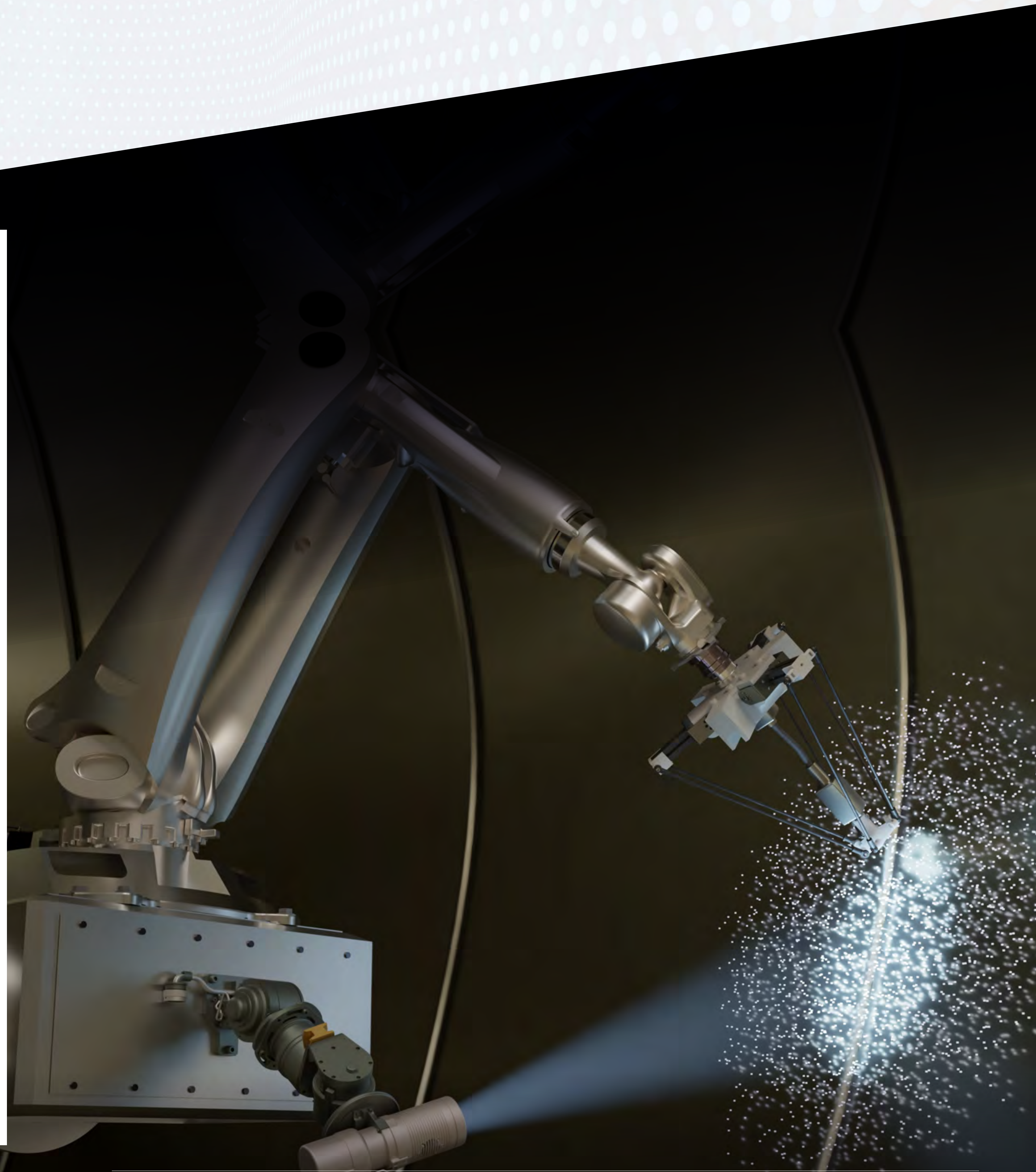
Technology for rapid intervention and in-situ repair must operate quickly to minimise downtime. This calls for the development of small cross-section systems able to operate through vacuum barriers, with designs that minimise the need to deploy vulnerable components into the vessel – particularly electronics and motors. This would enable equipment to better withstand the most extreme conditions present in fusion.
Ideally intervention systems should be the same as those used for regular maintenance to reduce system complexity. Rapid interventions are likely to involve inspection and survey including visual inspection, high-sensitivity geometric measurement and in-situ repair.

Critical topics

1. How systems can be designed to withstand extreme conditions.
2. How highly accurate inspection can be carried out in-situ.
3. How repair processes can be carried out reliably, safely and remotely.
4. How to develop planning and decision support systems that can be adapted to different types of failure so that the process of inspection does not create further unwanted impact.

Example research areas

- Systems for rapid inspection in extremely high thermal, vacuum, and radiation fields using novel structures and actuation methods
- Methods for highly accurate in-situ geometric metrology to detect erosion and deposition
- Methods for in-situ additive repair of metallic reactor components
- Surface cleaning and contamination removal



Challenge 8:

Maintenance productivity

Fusion power plants are complex systems that need to operate for decades to provide a viable return on investment. A plant must remain reliable and available to provide sustained electricity generation. This will require regular maintenance periods, which need to be as short as possible to maximise plant uptime.

Currently envisaged maintenance regimes for fusion plants indicate maintenance durations longer than desirable due to the large numbers of sequential actions, the transport logistics for components and maintenance equipment, and the durations required for shutdown, maintenance and restart processes. Additionally, where these must use "human-in-the-loop" approaches they are limited by human capacity.

Maintenance systems must also be adaptable to unscheduled events requiring rapid intervention. Maintenance productivity has a significant impact on life-time cost.

Critical topics

1. How to optimise maintenance and inspection tasks.
2. How to optimise designs and sequence tasks to minimise down time.
3. How to inspect and maintain systems so that lifetime operation is maximised.

Example research areas

- Novel instrumentation enabling efficient maintenance operations
- Dynamic schedule optimisation algorithms
- Faster deployment devices
- Rapid service connection mechanisms and processes
- Time-efficient remote maintenance operations, for example pipe cutting and welding
- Automation of common, dexterous handling tasks

Challenge 9:

Waste management

Operating a fusion plant creates waste: as a product of the fusion process, from parts taken out of service, when decontaminating components, and on completion of a maintenance cycle.

Waste management technology needs to handle all forms and grades of waste and it must be able to assess the level of contamination on surfaces and components. In particular, assessing and maintaining cleanliness in-vessel is critically important given its impact on operational efficiency.

Disposal must be done safely and in compliance with hazardous material regulations. The long-term goal is to find non-destructive, low-waste processes for disassembly, decontamination, maintenance and reassembly.

The primary challenges include optimal size reduction, the packing of complex composite in-vessel components, the detection and characterisation of waste, the sorting and segregation of waste, and the detritiation of components. Minimising the unnecessary progression of waste into higher waste categories is a key objective.

Solving these challenges is critical for safe and efficient waste management. Because waste processing and part refurbishment have an impact on operating costs, they must be carried out economically with respect to both material use and operational downtime.

Critical topics

1. How to optimise waste handling and keep within regulatory requirements.
2. How to refurbish and process parts including detritiation.
3. How to accurately assess, remove and dispose of contamination.
4. How to process, segregate and grade complex waste using remote systems.

Example research areas

- Autonomous dexterous handling of complex waste components
- Methods for automatic contamination detection
- Methods for the detection and effective removal of surface contaminants from vessel components
- Methods for automated non-destructive disassembly of complex structures
- Regulation-compatible contamination estimation

Challenge 10:

Through-life cost reduction for long-lived facilities

Lifetime costs, including end-of-life costs, are a critical factor in the success of fusion-based electricity generation. Over its lifetime a fusion plant will have a high potential for loss of efficiency and suboptimal operations to drive up operating costs. These effects may be compounded over long lifespans by technology obsolescence and altered operational requirements that create unforeseen efficiency losses.

Minimising lifetime cost needs to be considered at design by standardising interaction processes, by minimising interaction complexity and by utilising technology to speed up interventions. Complex interactions are more likely to increase costs and increase training requirements for operators and engineering teams.

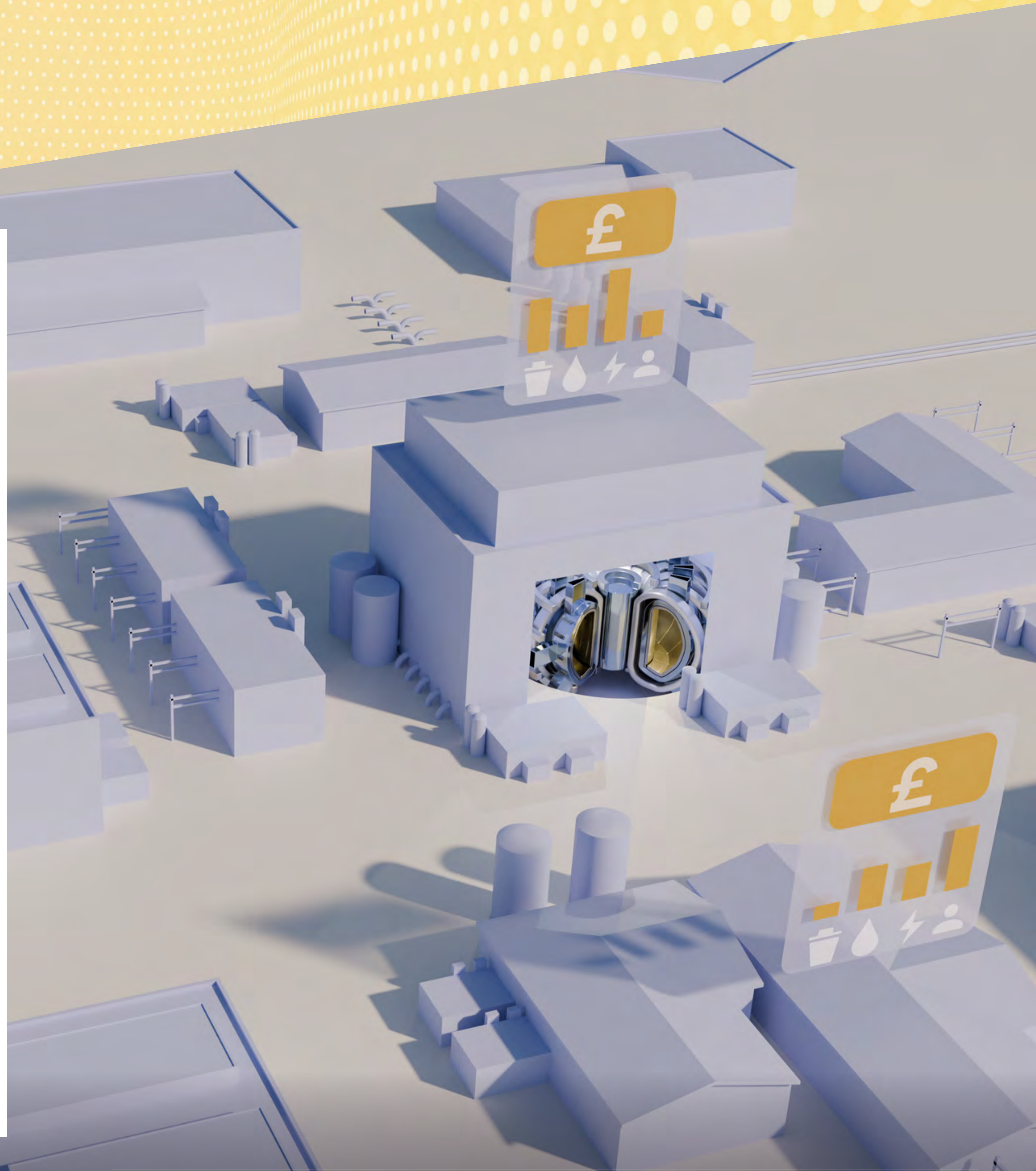
Cost-efficient decades-long operations will be built on the ability for teams and systems being able to adapt in a cost-effective way, to respond to changes in requirements and technologies.

Critical topics

1. Which technologies, methods and standards can help to reduce the overall cost of a plant over lifespans of several decades.
2. How to design for reduced interaction complexity, protect a plant from obsolescence, extend component life, and be operationally agile by adapting as requirements change over time.

Example research areas

- Technologies to speed up operations and reduce training needs
- Methods that enhance reusability of components
- Standards that assure quality and processes to future-proof and enable adoption of new technologies
- Highly intuitive human interfaces that rely on standardised approaches to increase operator familiarity
- AI based operations support systems that reduce the burden on the operator and enhance decision making



How RACE can support your work

Assistance with defining use cases and explaining impact
We are happy to advise your project, including helping to define how your research can benefit fusion energy, as well as helping to explain and quantify its real-world impact.

Access to expertise
We have over 350 experts in all aspects of fusion robotics engineering and operations, including a unique and highly experienced team of remote operations engineers who specialise in planning and performing remote robotic operations.

Access to physical facilities
We have a number of facilities available to academic research including robot platforms, sensors, and other test facilities that may be useful in supporting your work.

Access to data, software and digital models
Access to data and digital assets can be extremely valuable to robotics research. We have a collection of data and models that represent the unique challenges of fusion and related environments, as well as software platforms that may be of benefit to your research.

Funded PhDs
Each year RACE funds PhDs in areas of priority to the fusion mission. We would be happy to discuss any potential proposals, as well as support with promoting fusion-relevant PhD projects.

Hosting secondments and placements
We offer the opportunity for researchers to be immersed in the fusion robotics world by sitting alongside the RACE team. Secondment and placement opportunities are available at our Culham and Whitehaven sites.

Supporting experiments and deployments
We can support experiments with advice and equipment, as well as providing expert operators as participants. We may also be able to facilitate deployment trials in real or representative fusion environments.

Giving lectures and talks and supporting workshops
We are pleased to offer lectures and talks to your teams to explain fusion challenges and share our latest research, and can also participate in workshop sessions with our subject matter experts.

Feel free to contact us for an informal discussion on how you can contribute to solving key robotics challenges in fusion energy, or how we can assist in supporting your research.

contactus@race.ukaea.uk

The UK Atomic Energy Authority's mission is to lead the delivery of sustainable fusion energy and maximise scientific and economic benefit

UK Atomic Energy Authority

Find out more
www.gov.uk/ukaea

Contact us

- For collaboration opportunities
- To learn more about fusion research challenges
- To access test facilities
- To discuss support to fusion-relevant research projects

contactus@race.ukaea.uk

Follow @UKAEAofficial

CPS21.703