Remote-handling challenges in fusion research and beyond

Rob Buckingham and Antony Loving

Energy-producing nuclear fusion reactions taking place in tokamaks cause radiation damage and radioactivity. Remote-handling technology for repairing and replacing in-vessel components has evolved enormously over the past two decades — and is now being deployed elsewhere too.

In the search for a viable future electricity supply, nuclear fusion remains an enticing option[1,2]. While fusion physicists contend with the challenges of controlling high-temperature plasmas, fusion engineers have started to think about designing a cost-effective fusion powerplant. A fusion reactor has to be designed not only to contain the burning plasma, but also to capture and use the fusion energy that is produced in the form of energetic 14.1-MeV neutrons. Ultimately, this energy must be used to produce steam to drive an electricity generator. The only way to do this is to slow down the neutrons, hence harvesting the kinetic energy, by 'putting materials in the way'. These materials, notably metal 'blankets' containing lithium, and coolants such as water or helium, are placed adjacent to the plasma inside the vacuum vessel.

A major consequence of the generated high-energy neutrons hitting the obstructing materials is radiation damage[3,4]. Steel, for instance, which is used extensively in the construction of the vacuum vessel and support structures, becomes more brittle when irradiated. Hence such material components will need to be regularly inspected and potentially repaired or replaced.

The extreme radiation also means that all operational and maintenance activities conducted within or near the vacuum vessel have to be carried out using remotely operated tools. Initial analysis indicates that taking such remote interventions into account will be fundamental to the design of fusion power plants[5,6]. Currently, it is predicted that fusion reactors will be more expensive than equivalent-output fission reactors. This is in large part due to the increased complexity of operation and maintenance tasks.

With great foresight, the designers of the Joint European Torus (JET) in Culham, UK, operated by the UK Atomic Energy Authority (UKAEA), included a full remote-handling capability[7]. Over the past

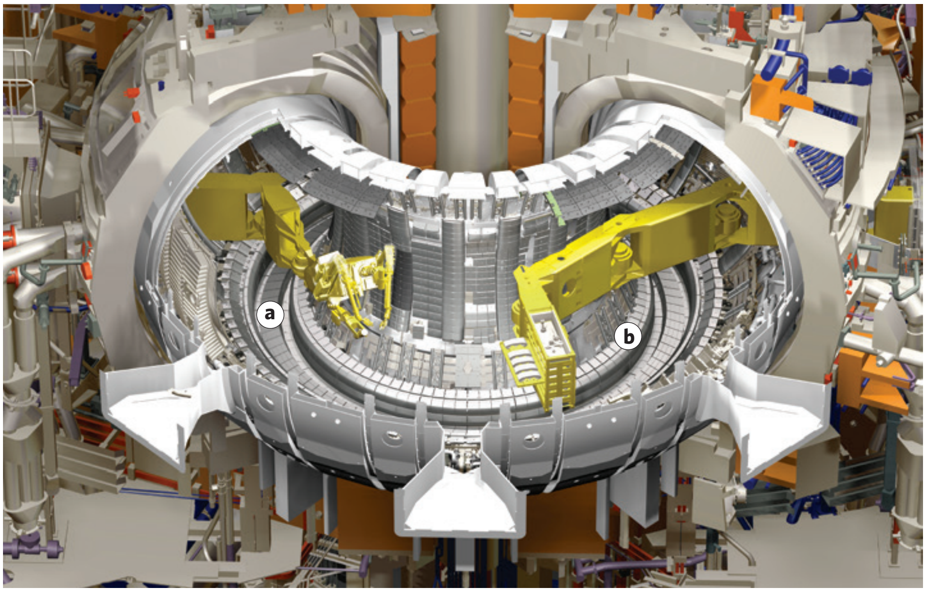

Figure 1 | Remote-handling systems used to service the JET tokamak. **a**, Articulated transporter with servo manipulator, used for performing maintenance operations. **b**, Articulated transporter with component/tooling delivery system. Both robotic arms enter the vessel through equatorial ports and can reach any place within the tokamak vessel.

20 years, UKAEA has developed the tools[8,9] and know-how to maintain and upgrade the JET device and also to better understand the remote-handling challenges for future devices. The team now has more than 30,000 hours of real operational experience.

The JET remote-handling system uses 'man in the loop' force-feedback master–slave servo manipulators. This means that the operator physically controls where the manipulator moves and can feel the forces being exerted on the slave. The main manipulator, which is 12 m long and has a 500-kg payload, is able to access all parts of the JET vessel from an enclosure that is attached to the JET vessel at the beginning of an intervention period. This offers the operator flexibility and efficiency in undertaking many different tasks inside JET, for instance first-wall maintenance (the first wall comprises many thousands of individual tiles) including inspection, tile removal and attachment, cutting, welding, diagnostic alignment and cleaning. The haptic (real-time force-feedback) system gives the operator a valuable sense of 'feel', and a full three-dimensional virtual reality environment along with camera images creates the sense of virtual presence. A second system delivers tools and components to the workplace, working closely in tandem with the main manipulator (see Fig. 1).

Remote handling in future fusion reactors, such as ITER[10], and power plants will be more challenging, however, because of the need to replace lithium breeding blankets — similar to the way fuel rods have to be replaced in a nuclear fission reactor.

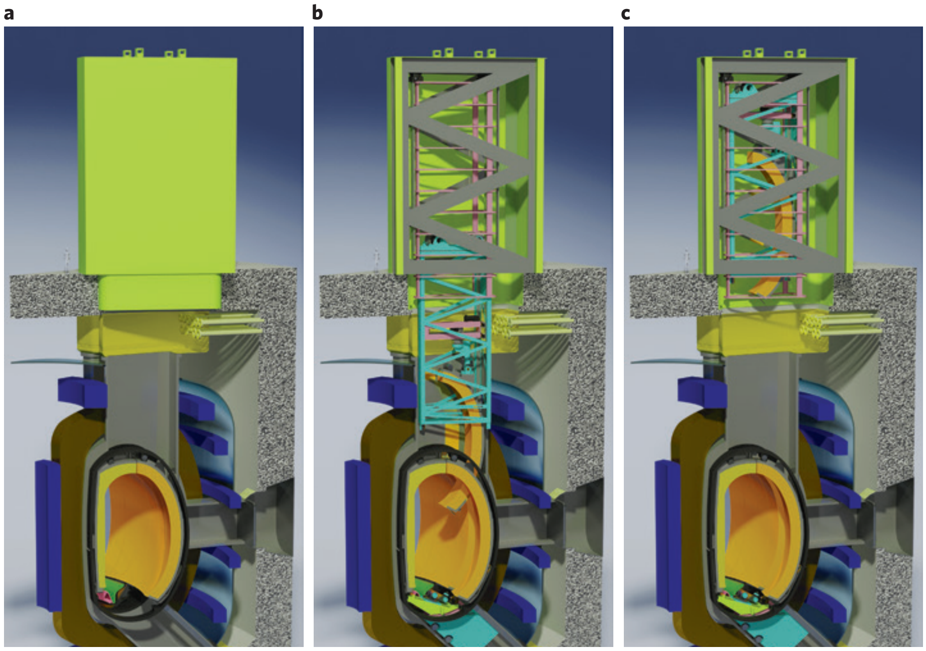

Figure 2 | Tokamak blanket segment removal. **a**, A transport cask (green) containing a blanket transporter is docked to the tokamak. **b**, An 80-tonne blanket (orange) is removed. **c**, The blanket is contained within the transport cask, ready for either repair or disposal in the active maintenance facility, which consists of a number of confinement cells (hot cells) to aid in maintenance of activated/contaminated components and remote-handling equipment, storage of activated components and waste processing. Images © UK Atomic Energy Authority and EUROfusion.

Typically, around 80 curved breeding blanket segments, each ~12.5 m long and weighing up to 80 tonnes, will be contained within the main vacuum vessel. As well as slowing down the neutrons and channelling away the fusion energy through heat exchangers, these blankets breed tritium for the main fuel cycle as the neutrons bombard the lithium. Replacing the blankets once the lithium has been used up entails them being removed and replacements inserted through vertical ports in the vessel between the confinement magnets (Fig. 2). As they are actively internally cooled, as part of the primary cooling circuit, cooling pipes must be disconnected when a blanket segment is removed. Similarly, when inserting a new blanket, the coolant pipes must be re-welded to strict nuclear standards. A complication is that neutron-damaged steel is extremely difficult to weld because the voids created within the steel get filled by hydrogen atoms[11]. These blanket segments have to be accurately positioned (±10 mm) to avoid neutron leakage that would otherwise cause damage to the reactor vessel and external components, most notably the superconducting magnets (generating the magnetic fields required for plasma confinement).

Another component of a tokamak requiring routine remote handling is the divertor, which can be thought of as the exhaust system of a fusion reactor. The fusion of deuterium and tritium produces alpha particles (helium nuclei) as well as energetic neutrons. Although these alpha particles are needed for heating the plasma, in time they must be partly removed to avoid fuel dilution. This is achieved by shaping the magnetic field lines so that they scrape the outer surface of the plasma into the divertor region, where the exhausted particles are cryogenically pumped away. Because the divertor will be subject to continuous plasma contact (the power densities in JET are calculated to be ~10 MW m^{-2}), the resulting rate of erosion means that the divertor components will also have to be remotely exchanged regularly[12] (Fig. 3).

Remote-handling research is now being driven by issues that will be relevant to fusion-reactor architecture. These include:

(1) Combining the many causes of material deformation — static and dynamic loads, radiation, decay heat, neutron deformation, magnetic loads and heat flow — into a single analysis tool. Such analysis is relevant to both the in-vessel components and the large manipulators that will be required to manoeuvre the components. Neither can be made rigid enough that such deformations can be ignored.

(2) Developing remote techniques for welding long non-straight pipes. Laser welding is the strongest candidate, with the main challenges being size reduction of the tool head and delivering the tools to and from the weld site while guaranteeing recovery of any temporarily installed equipment.

(3) Ex-vessel operations. Although the focus of this Commentary is on replacing in-vessel components, the logistics of delivering tools, removing radioactive components into storage, and then introducing clean or refurbished components is also a considerable challenge.

(4) Safety and recovery systems that must be designed to meet the relevant nuclear regulations and codes of practice. Although not directly relevant to in-vessel operations (these will be largely automated), ex-vessel remote-handling equipment will ideally be semi-autonomous, using sensors to modify actions including changing the trajectory of moving elements.

(5) Fusion codes of practice and standards. It is likely that processes and standards developed for other remote-handling activities will not be appropriate for fusion. Therefore, it will be necessary to revisit these and solve safety issues in the most cost-effective manner.

All of these issues are compounded by heat and radiation at every stage of the operation. The energetic neutrons raise the temperature of the inner surfaces of the breeding blankets to approximately 500 °C, and gamma radiation emitted by activated materials will generate considerable dose rates during maintenance operations. Calculations show that replacement of all in-vessel plasma-facing components will take many months of continuous operation[13]. This is a key parameter that affects plant utilization, and hence affects the cost of electricity. Recovery from a failure of the remote-handling systems is a particularly challenging issue.

Clearly, many challenges remain to be overcome, which is why the UKAEA's Remote Applications in Challenging Environments (RACE) facility was created. This new centre at Culham, UK, will provide state-of-the-art large-scale, long-term testing facilities, remote-handling equipment and design expertise for developing the design of fusion reactor remote-handling systems. Important contracts have been landed already, most notably in relation to ITER remote-handling facilities.

Outside fusion, robotics in all its forms is an emerging market. Fusion will benefit greatly from developments in sectors as

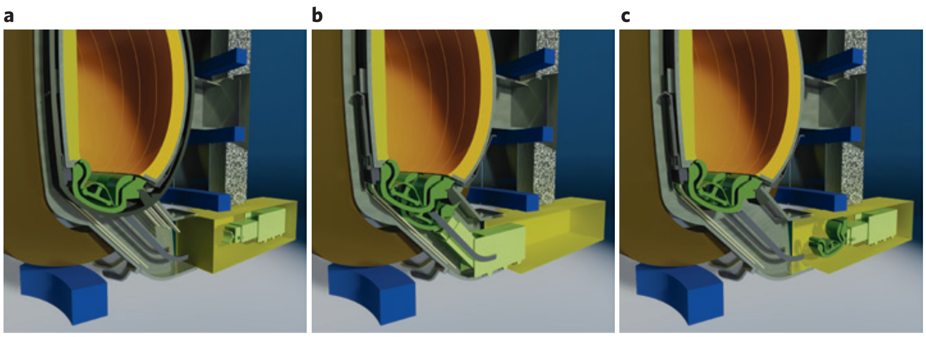

Figure 3 | Tokamak divertor cassette removal. **a**, A transport cask docked to the tokamak. **b**, A divertor cassette is removed. **c**, The divertor cassette is in the cask, ready to be removed to the active maintenance facility. Images © UK Atomic Energy Authority and EUROfusion.

diverse as autonomous cars and remote inspection of oil refineries. Apart from being a UKAEA facility, RACE is part of the EUROfusion family (the European Consortium for the Development of Fusion Energy) and will draw on a wealth of industry expertise from UK companies and research organizations as well as international collaborations.

It is envisaged that RACE expertise will be useful for many different industries with an interest in robotics and autonomous systems. Small-to-medium enterprises and multinationals alike need development centres like RACE to help to address pre-commercial technical risks. This is already being demonstrated, with RACE managing the supply of hot-cell remote-handling equipment used to handle the highly active targets for the European Spallation Source currently under construction in Lund, Sweden. This broader activity is also part of the aim of generating a shorter-term return from investment in fusion.

Delivering fusion power is still a grand challenge and will take an exceptional, determined team of physicists and engineers to find a winning solution. We will need to draw on developments made across industries from construction, where precision placement of large components is routine, to rocket and aero engines that use materials that function at extreme temperatures. Human creativity and need will continue to drive the progress of remote-handling technologies over the coming years. This, coupled with a symbiotic relationship with fusion physicists and reactor designers, provides the best route to achieving viable fusion electricity. ❐

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