(Em)Powering the End of Power: HRI for Safe Nuclear Decommissioning

Anne-Marie Oostveen
Centre for Robotics and Assembly, Faculty of Engineering and Applied Sciences
Cranfield University
Cranfield, United Kingdom
j.m.oostveen@cranfield.ac.uk

Jingyi Zhang
Centre for Robotics and Assembly, Faculty of Engineering and Applied Sciences
Cranfield University
Cranfield, United Kingdom
jingyi.zhang2@cranfield.ac.uk

Sarah Fletcher
Centre for Robotics and Assembly, Faculty of Engineering and Applied Sciences
Cranfield University
Cranfield, United Kingdom
s.fletcher@cranfield.ac.uk

Abstract

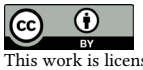
As fusion research facilities like the Joint European Torus reach the end of their operational lives, the need for safe and precise decommissioning has become critical. Human-Robot Interaction (HRI) technologies are central to reducing human risk and enabling complex remote operations in hazardous environments. Based on an exploratory study with experts from the UK Atomic Energy Authority and the International Thermonuclear Experimental Reactor, this paper examines current and emerging uses of teleoperated manipulators, articulated booms, virtual reality, and force feedback systems in fusion decommissioning. The findings highlight key insights into training, cognitive load, and ethical considerations in operator data use. HRI emerges not just as a technical solution but as a vital enabler for empowering society to transition responsibly away from legacy energy infrastructures.

CCS Concepts

•Human-centered computing~Human computer interaction (HCI)~HCI design and evaluation methods •Human-centered computing~Interaction design~Interaction design process and methods

Keywords

Human-Robot Interaction (HRI), Nuclear Decommissioning, Fusion Energy, Teleoperation, Operator Safety



This work is licensed under a Creative Commons Attribution International 4.0 License.
HRI '26, Edinburgh, Scotland, UK
© 2026 Copyright is held by the owner/author(s).
ACM ISBN 979-8-4007-2128-1/2026/03
https://doi.org/10.1145/3757279.3788661

ACM Reference Format:

Anne-Marie Oostveen, Jingyi Zhang, and Sarah Fletcher. 2026. (Em)Powering the End of Power: HRI for Safe Nuclear Decommissioning. In Proceedings of the 21st ACM/IEEE International Conference on Human-Robot Interaction (HRI '26), March 16–19, 2026, Edinburgh, Scotland, UK. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3757279.3788661

1 Introduction

The end of a nuclear reactor's life is not the end of its risks. While fusion energy offers a cleaner alternative to fission, fusion facilities pose distinct technical, logistical, and human challenges during decommissioning [1,2]. Unlike fission reactors, which benefit from decades of standardized dismantling practices, fusion systems such as the Joint European Torus (JET) and the International Thermonuclear Experimental Reactor (ITER) are still pioneering both operational and post-operational processes [3,4]. Fusion decommissioning requires managing radioactive materials such as tritium, navigating large-scale yet tightly confined geometries, and mitigating contamination from toxic substances like beryllium, making direct human intervention impractical or unsafe [5,6]. As a result, advanced Human-Robot Interaction (HRI) systems are essential for remotely conducting inspection, maintenance, and dismantling tasks [7,8].

This paper examines the role of HRI in enabling safe fusion decommissioning through expert insights from a Principal Control Engineer and a Senior Remote Handling Operations Engineer working at JET and ITER. Drawing on their experience, we examine how teleoperated manipulators with force feedback, virtual reality-based planning tools, and team-based control room operations support safe work in highly hazardous environments, alongside the roles of training, operator variability, and ethical system design.

This paper is structured as follows. Section 2 provides background on nuclear decommissioning; Section 3 describes the interview-based methodology and analysis; Section 4 presents the findings; Section 5 discusses implications for HRI design and future reactor projects; and Sections 6 and 7 conclude with key contributions and limitations.

2 Background

2.1 Fusion Energy and Decommissioning Challenges

Nuclear fusion is a promising low-carbon energy source in which light atomic nuclei combine to release large amounts of energy, offering advantages over fossil fuels and nuclear fission in terms of safety and long-lived waste production [1-4]. Current fusion research relies primarily on tokamak reactors that use strong magnetic fields to confine plasma at temperatures exceeding 100 million degrees Celsius [5,1]. While sustained net energy gain has not yet been achieved, major projects such as the Joint European Torus (JET) and the International Thermonuclear Experimental Reactor (ITER) continue to advance fusion science, with the Demonstration Fusion Power Plant (DEMOS) intended to bridge experimental systems and commercial deployment [2,6].

As fusion facilities reach the end of their operational lifetimes, decommissioning has emerged as a critical challenge. Despite fusion's reputation as a "clean" energy source, reactor components accumulate radiological and chemical hazards through neutron activation, tritium contamination, and the use of toxic materials such as beryllium [6,9,10]. These risks make direct human intervention unsafe, requiring decommissioning to be conducted remotely using robotic systems. Early facilities such as JET were not designed for remote dismantling, resulting in constrained access and complex geometries, whereas newer projects including ITER and UK STEP increasingly treat decommissioning as a design constraint rather than an afterthought [10]. Prior nuclear decommissioning research highlights the consequences of reactive planning and insufficient integration of safety, technology, and organizational factors [11,12]. Fusion decommissioning therefore offers an opportunity to embed remote handling, maintainability, and human-robot collaboration into system design from the outset, positioning fusion as a critical testbed for HRI in safety-critical domains.

2.2 HRI in Safety-Critical Teleoperations Domains

HRI has been widely studied in safety-critical domains where robots act as proxies for humans in inaccessible, hazardous, or time-critical environments. Across these domains, the central challenge is not full autonomy, but robust human-in-the-loop teleoperation that supports precision, situational awareness, and accountability under severe risk [13,14].

Within nuclear decommissioning, prior work highlights challenges associated with long-reach teleoperation, degraded sensing, and constrained geometries. Zhang et al. [15] show that safe fuel-debris retrieval at Fukushima Daiichi depends on conservative motion strategies, stable control architectures, and continuous operator oversight. Talha et al. [16] demonstrate through human-factors experiments that operator performance is strongly shaped by interface design, feedback calibration, and task predictability rather than robotic capability alone. Vitanov et al. [17] further emphasize the importance of reliability, controllability, and recovery from failure over speed or autonomy when direct human intervention is impossible.

Comparable challenges arise in military explosive ordnance disposal (EOD), where teleoperated robots are used to inspect and neutralize explosive threats. Research in this domain stresses intuitive control mappings, high-quality visual feedback, and operator trust in situations where small errors can have catastrophic consequences [18,19]. Surgical robotics provide a further relevant comparison, particularly for telemanipulation systems employing force feedback. In minimally invasive and telesurgical procedures, haptic feedback and motion scaling enhance precision while preserving surgeon agency, though poorly tuned feedback can increase cognitive and physical workload [20,21]. Similar trade-offs have been reported in nuclear teleoperation studies [16,17].

Across nuclear decommissioning, military EOD, and surgical robotics, HRI research converges on core principles: the primacy of human authority, cognitively sustainable interfaces, the value of simulation and rehearsal, and the ethical importance of transparency and accountability [14,22].

2.3 The Central Role of Human-Robot Collaboration

Building on these cross-domain insights, human-robot collaboration in fusion decommissioning emerges not as an isolated technical solution, but as a domain-specific instantiation of established safety-critical HRI principles. In nuclear decommissioning, environmental variability and access constraints have driven the adoption of teleoperation systems that allow operators to work at a safe distance from radiation and falling debris [23,24]. Research has focused on improving manipulator dexterity, sensing, and autonomy for tasks such as cutting, sorting, and radiological surveying, alongside interface design for teleoperation displays, haptic masters, and visualization layouts [25,26].

At JET, for example, human-robot collaboration systems enable operators to manipulate tools with millimeter precision inside radioactive environments from a control room using articulated booms, force-feedback manipulators such as MASCOT, and simulation environments based on digital twins and Virtual Reality [27]. Despite increasing technical capability, operators continue to perform cognitively demanding coordination and decision-making tasks due to gaps in human-centered integration across sensing, control, and interface modules [28,29].

Human-robot collaboration in this context is therefore a socio-technical system shaped by organizational norms, ethical values, and design choices. Prior work underscores the value of simulation environments that support learning and safety without introducing stress or surveillance [27], while emphasizing the need to balance automation and human authority in high-risk settings [13]. From a Science and Technology Studies perspective, such systems are co-produced by social actors, material constraints, and institutional logics [22,30]. Decisions about feedback, data collection, and control-room organization thus encode priorities around accountability, risk, and empowerment,

ultimately shaping how fusion decommissioning is conducted and perceived.

Taken together, this evolving body of work shows that human-robot collaboration is not a peripheral concern but a central enabler of safe, effective, and sustainable nuclear fusion decommissioning. It bridges the technical demands of robotics with the lived experience of human operators and the ethical imperatives of long-term nuclear stewardship. In fusion's transition from experimental science to infrastructure, human-robot collaboration stands as a crucial mediator between machine and operator, between risk and resilience, and between the past and future of energy systems.

3 Methods

To investigate the practical and societal roles of human-robot collaboration in nuclear fusion decommissioning, we employed a qualitative research design based on systematized expert interviews, a form of semi-structured interviewing aimed at eliciting experts' technical and process knowledge [31]. This approach is well suited to highly specialized, safety-critical, and access-restricted domains where direct observation and large-scale sampling are infeasible.

3.1 Participants

Two domain experts with direct responsibility for robotic operations at the Joint European Torus (JET) and ITER participated in the study. The first participant, the engineer, is a Principal Control Engineer at the UK Atomic Energy Authority (UKAEA), responsible for recent upgrades to JET's robotic systems and the conceptual design of remote handling systems at ITER. The second participant, the operator, is a Senior Remote Handling Operations Engineer with over five years of hands-on experience operating robotic booms and the MASCOT manipulator at JET and is currently seconded to ITER to review component design for remote maintainability.

The small sample size was a deliberate methodological choice consistent with qualitative research in high-risk, high-expertise contexts, where expertise is rare and highly concentrated. Together, the participants provide complementary system-level and operational perspectives from the only active robotic decommissioning of a tokamak and the design phase of ITER. Following Braun and Clarke [32,33], such information-rich cases are sufficient when the aim is to surface expert practice rather than achieve statistical generalization.

3.2 Interview Protocol

The JARVIS project received funding from the EU's Horizon Europe research and innovation program under grant agreement no. 101135708

Semi-structured interviews were conducted online in English via video conferencing, lasted 1:07 hours (operator) and 1:23 hours (engineer), and were recorded and transcribed verbatim, resulting in 67 pages of data. A pre-designed interview guide ensured coverage of core topics while allowing flexibility to pursue emergent issues. Themes included nuclear operations and risks, human-robot collaboration and interface design (e.g. feedback modalities and required skills), training and team integration, and ethical considerations such as responsibility, trust, and human oversight.

All participants provided informed consent and were assured anonymity in compliance with the EU GDPR and the UK Data Protection Act. Identifiers were removed from transcripts, data were securely stored on password-protected systems at Cranfield University, and no identifiable information was shared with third parties.

3.3 Data Analysis

Data were analyzed using thematic analysis [32,33]. Transcripts were first read in full and descriptively coded, then analyzed through iterative cycles of coding and theme development. An initial set of 81 codes was refined into 24 higher-level codes and synthesized into five final themes. Theme development was supported through ongoing reflexive discussion among the authors. Given the small expert sample, intercoder reliability metrics were not calculated; instead, analytical rigor was ensured through reflexive review and collaborative interpretation, consistent with established qualitative standards [33,34].

4 Results

Thematic analysis identified five domains in which HRI shapes nuclear decommissioning: remote manipulation, interface and feedback design, training and human variability, operational challenges, and ethical considerations.

4.1 Theme 1: Remote Manipulation Technologies

HRI in nuclear fusion decommissioning is centered on advanced teleoperation systems that allow precise, remote-controlled work in highly hazardous environments. At the Joint European Torus (JET), two articulated booms are deployed inside the torus vessel alongside a sophisticated force-feedback manipulator known as MASCOT. These systems allow operators to perform complex physical interventions entirely from a control room. The engineer interviewed explained that the robotic systems are fully teleoperated, with *"no automation in the sense that it would do it by itself."* Operators guide the equipment through direct manual inputs, making MASCOT a *"1:1 hand controller with 14 axes."* This means, as he clarified, *"whatever moves they make, the remote does at the same time."* This allows for real-time, intuitive control, particularly essential in the confined and geometrically complex environment of the reactor.

MASCOT's capabilities were emphasized repeatedly: *"It can do similar payloads to a person and similar operations,"* noted the operator. Crucially, it offers tactile, haptic feedback, giving operators a physical sense of interaction with the remote environment. *"You move the robot in the air, but feel that tile, unbolt it with a tool, and feel the weight of that tile and place it in a bucket."* This level of realism is indispensable for delicate tasks like extracting tiles or handling tritium-contaminated parts. The boom arms and MASCOT are not joystick-controlled but use manual

manipulators to simulate natural hand movements. According to the engineer, operators can perform highly fine-grained tasks: *"You can trace the edge of an A4 paper using MASCOT; they can tell where it is based on that haptic feedback."* This precision is especially important when manipulating sensitive instruments or operating within tight spatial tolerances.

Beyond raw dexterity, the system also includes assistance features. Operators can direct the system to a specific location, and the robot will autonomously follow a predefined trajectory to that point, eliminating the need for manual adjustment of every joint. *"We can say 'I want to go to this point,' and the machine will just go to that exact point,"* said the engineer. These features support efficiency while maintaining operator control. Although JET was not originally designed for robotic maintenance, retrofitted upgrades have enabled the robotic systems to function effectively. *"JET was not originally designed to be remote decommissioned,"* the engineer explained. The geometry of the reactor adds further complexity. The operator illustrated: *"The machine looks like a doughnut, and we kind of enter from one of the sides and we are inside where the filling of the doughnut would be."* The booms are designed to *"snake"* into this space, allowing tools and manipulators to reach targets deep inside the vessel.

These remote manipulation systems are designed for robustness as well as finesse. *"If you apply too much pressure, you can break the wire over time… we have indicators that show when you're over-gripping,"* said the engineer. Despite the strength of the equipment, careful feedback mechanisms ensure that operators stay within safe force thresholds. Ultimately, these technologies allow operators to carry out intricate, physically demanding, and potentially dangerous tasks, without ever entering the radiation zone. The robotic systems at JET are the first of their kind used in full fusion reactor decommissioning. The operator highlighted that, while robotics is increasingly being applied to nuclear maintenance, its use in decommissioning tasks remains relatively new. *"There's not that much decommissioning that's done by robotics at the moment,"* she observed. As a result, there are still many unknowns and evolving practices in this area. One of the most pressing concerns is managing radiation exposure, particularly as it affects equipment over time. Unlike active operational environments where radiation levels and processes are well-characterized, decommissioning scenarios can be more unpredictable. *"One of the big ones is knowing the levels of radiation… and the degradation of equipment that comes with that,"* the operator explained. As the engineer concluded: *"JET is the first and only tokamak to be decommissioned with robots."* Other reactors have been sealed in concrete or abandoned without structured decommissioning strategies, which he characterized as wasteful and uninformative. In contrast, JET offers a rare opportunity to observe and refine robotic decommissioning practices in a real-world context.

4.2 Theme 2: Feedback and Interface Systems

Remote manipulation in fusion decommissioning depends not just on mechanical precision but on the design of interface systems that mediate the interaction between humans and machines. At JET, human-robot collaboration involves a sophisticated combination of real-time visual feedback, haptic (force) feedback, and selectively applied auditory cues, all designed to optimize operator control while managing cognitive load.

According to both interviewees, visual input is the most critical feedback modality. Operators rely on multiple video feeds from internal cameras mounted on the booms and the manipulator itself. These are displayed on a suite of monitors in the control room, allowing for continuous visual tracking of the robot's position, surroundings, and tool orientation. *"You need to be able to see what you're doing,"* said the operator. *"How you see it is a bit more flexible."* To support this visual workflow, the Human-Machine Interface (HMI) is carefully standardized. The engineer explained: *"Once you learn one system, it's consistent across all the systems… You don't have to learn three different systems."* This consistency is critical in high-pressure environments, where switching between boom controls and manipulator controls must be seamless.

Interface feedback is intentionally multimodal. The engineer described their layered approach: *"We try for multimodality… color plus symbol plus text if it's above a certain limit."* For example, simulation environments are marked in pink, while green indicates a live system axis. Icons and text overlays reinforce these visual cues, helping operators quickly interpret system status. This combination of visual and symbolic input supports rapid situational awareness and error prevention. The goal is not simply to provide more information, but to deliver the right information in the most actionable form based on human-centered design principles. *"We're looking for the value of the feedback rather than the quantity,"* the operator stated. This principle underpins interface decisions ranging from control layout to alert design.

The force-feedback system in the MASCOT manipulator is a core part of the HRI setup. It provides operators with a tactile sense of resistance, pressure, and weight as if they were physically interacting with the reactor environment. This allows for precision gripping, controlled unbolting, and damage-sensitive manipulations. Yet this haptic feedback is not used continuously. *"Yeah, it can be quite draining because you've got quite a lot of information that you're trying to process,"* the operator explained. In some cases, the team disables haptics to reduce cognitive or physical fatigue. The operator makes this decision based on task type, shift length, and personal working style. This flexibility reflects a broader philosophy of human-centered design.

Auditory feedback was tested but ultimately set aside. *"They had microphones… but there wasn't that much benefit from it and there was just generally more noise in the control room that wasn't actually benefiting the team,"* the operator recalled. The auditory overload detracted from team focus and added unnecessary stress, particularly during time-sensitive shutdowns. As a result, auditory channels are now used sparingly, if at all.

Feedback systems are designed with long operations in mind. Operators may spend hours at a time guiding robotic arms through delicate procedures, which impose both mental and physical demands. The design of interfaces, including screen layout, button logic, and grip ergonomics, takes this into account. *"There's a lot going on at once… having consistency and knowing what to expect helps a lot,"* the operator said. This is especially

important during emergency scenarios. Operators must be able to react instantly to unplanned situations, such as tool collisions or grip failure, without searching for controls or second-guessing system state. The multimodal interface helps enhance human cognitive processing and mitigate those risks.

4.3 Theme 3: Training and Human Variability

HRI in nuclear fusion decommissioning is only as effective as the people operating it. The systems used at JET are highly complex and demand not just technical knowledge, but deep operational fluency, psychological readiness, and team cohesion. To address this, UKAEA has developed a layered, formalized training program that accommodates both procedural standardization and individual learning styles.

The training process is staged across multiple environments, starting in a virtual simulation and progressing to hands-on control of real equipment. As the operator explained, *"We have an environment that is one-to-one with the actual JET vessel... we use our digital twin environment first."* This digital twin allows operators to practice tasks in a VR model that mirrors the live machine's geometry and constraints. It helps them understand spatial limitations, anticipate errors, and mentally rehearse operations. After VR training, operators transition to the In-Vessel Training Facility, a full-scale physical replica of the reactor where real equipment can be used in a safe, non-radioactive setting. *"We have a training facility where our robots can physically come inside... you can really learn by doing,"* the operator said. This environment replicates all major equipment, tools, and camera views, offering a zero-risk setting to practice tool handling and coordination. Only after demonstrating proficiency in these mock environments are operators cleared to participate in live operations on the active system.

Training is not limited to full operation rehearsals. It also includes a range of skill-testing activities such as puzzle boxes, virtual mazes, and object manipulation challenges. *"It can be representative things and fun things to kind of break it up a little bit and test the skills,"* said the operator. These exercises help assess and develop dexterity, spatial awareness, and coordination under pressure. Operators must also complete safety-critical training, which includes developing the confidence and authority to halt operations immediately when necessary. The ability to activate an emergency stop is treated not just as a procedural task, but as a fundamental aspect of operator responsibility. This emphasis on situational control and decisiveness is embedded into the training culture from the outset, ensuring that individuals understand both their technical role and their safety authority.

Live operations are rarely done solo. *"On average, four and a half operators are needed to do operations at JET,"* said the engineer. A typical remote handling team includes a MASCOT operator, a boom arm controller, a camera coordinator, an HMI operator, and a supervisor. Communication, timing, and task division are essential for successful execution. Training is therefore also team-based and designed to mimic real control room dynamics. *"Sometimes if there is a lot of work to do, it will naturally fall to the people that fit those roles better,"* explained the operator, but teams regularly rotate roles to prevent over-dependence on individual specialists and to promote knowledge transfer. Cross-functional training ensures redundancy, resilience, and flexibility within the operations crew.

The pathway to becoming an independent operator varies but generally requires six months. *"That's more the control room environment and working as a team,"* said the operator. Hands-on tool familiarity and simulator work may take only four weeks, but full integration into a live team requires behavioral readiness and environmental awareness. A formal training matrix defines four proficiency levels: 'Trainee', 'Intermediate', 'Advanced', and 'Trainer'. Each level is associated with specific expectations, skill sets, and responsibilities. As the operator explained, "We don't want the one person who's amazing at this equipment, if they're sick, then we can't do anything."

The system also allows for individual working preferences. *"It is a very personalized thing... there's always something that someone can be an expert in and have their skill shine, which is good,"* the operator said. Some team members may prefer visual over haptic feedback; others may excel at sequencing operations or interpreting video feeds. The system design and team structure allow for such preferences to coexist, rather than enforcing one-size-fits-all procedures. This respect for operator individuality not only improves morale but also enhances system performance, allowing each team member to contribute their strengths to complex, high-stakes tasks.

4.4 Theme 4: Operational and Environmental Challenges

Decommissioning fusion reactors like JET and ITER poses a set of operational and environmental challenges that are fundamentally distinct from traditional fission plants. As these machines operate, high-energy neutrons activate structural materials, increasing residual radiation and requiring a cool-down period before any remote work can begin. Other challenges include hazardous materials, complex internal geometries, extreme component scales, and the pressure of narrow shutdown windows. HRI systems must operate effectively within, and sometimes despite, these constraints.

Tritium, a radioactive isotope of hydrogen used in fusion fuel, presents a major challenge. It is hazardous both chemically and radiologically and permeates materials in the reactor environment. As the engineer explained, *"Tritium is a nice material in the sense that it doesn't have the half-life of uranium... But it's hydrogen, it's explosive, and it's radioactive, emitting alpha particles. So you cannot have people around it."* He added, *"There's tritium in the dust."* These conditions render human presence inside the vessel unsafe during or shortly after operations, making full robotic access not just preferable but mandatory. Beryllium, used in the reactor tiles, introduces an additional risk through dust contamination. The operator noted that these materials are *"very light and powdery"* and that proper containment is essential to avoid both toxic exposure and cross-contamination of reactor systems.

Even though fusion produces less long-lived waste than fission, neutron irradiation still takes a toll on nearby systems. The robot components themselves must be carefully managed to avoid

degradation. *"While this machine operates, it creates a lot of neutrons… the higher the machine, the longer the run, the higher the chances that you're frying your digital system,"* said the engineer. Radiation-induced damage most often appears in sensitive imaging systems. *"That's where we tend to see it first… pixelation, little dead pixels,"* said the operator. The engineer stresses the importance of either developing radiation-hardened robots or designing systems that allow for robotic components to be removed and replaced easily, noting: *"At the moment, the view is for decommissioning… you're looking at robots that you can move in and out of the reactor."* The robotic systems are installed only during maintenance windows and removed before the machine is restarted. This adds significant logistical overhead: *"It takes six weeks to install everything and remove everything in order to get remote handling,"* the engineer explained.

Fusion reactors contain some of the largest and most complex internal components in the energy sector. *"JET is a small machine with small components,"* the engineer explained, *"At ITER, we're looking at components that weigh up to 50 tons."* This physical scale rules out manual intervention entirely and challenges the capacity of even advanced robotic systems. The robots must handle massive parts with surgical precision, often within centimeters of fragile reactor surfaces. The engineer noted, *"In fission, you can lower a winch and pick up the spent fuel. In fusion, you don't have that ability."* Tooling and handling systems must be custom-designed, and the geometry of the vessel often requires bespoke paths and orientations for access. This complexity adds time, cost, and design uncertainty to every decommissioning task.

Unlike fission reactors that often allow straight-line access, fusion vessels like the JET tokamak require robotic systems to navigate a closed, toroidal space. This environment constrains not only where robots can go but also what angles are available for tool use. Manipulators must be designed to *"snake"* through small ports, bend into multiple axes, and perform tasks while staying clear of walls and other structures. The team often rehearses movements in simulation to verify that they are even physically possible.

Shutdown periods are the only time remote maintenance and decommissioning can occur, and they are strictly limited. "You have a very specific time window… and if you drop a screw, you have to find and pick it up," said the operator. Mistakes or delays have cascading effects, pushing back reactor restart and interrupting scientific or energy output schedules. The engineer framed this in economic terms: "You're not generating electricity while you're doing maintenance… the scientific cost is really about running the machine." Every minute of downtime matters, and robotic systems must be not only safe and precise, but also fast and fault tolerant.

4.5 Theme 5: Ethical Issues and Future Outlooks

As HRI systems become more capable, data-rich, and central to reactor operations, they bring not just technical complexity but ethical considerations as well. The experts interviewed highlighted several areas where ethics intersects with engineering: data privacy, surveillance, training metrics, team trust, and the evolving role of the human operator.

At JET, all robotic operations are recorded automatically via cameras mounted on the booms and the MASCOT manipulator. These recordings are an important tool for learning, reviewing performance, and identifying possible improvements. The operator described this as both helpful and empowering: *"All of our operations are recorded… I find it very useful because if I watch back an operation… I can tell I was looking at that screen for too long [points to the left], and if I'd just looked there [points to the right], I could have done it quicker."* However, both participants expressed discomfort at the idea of recording the operators themselves inside the control room. The operator was direct in her concern *"I'm not sure how I'd feel if it was in the control room… I just want to do my job in peace."* Surveillance, she noted, would alter the team's behavior in ways that could undermine both communication and performance *"If everyone thought they were being filmed all the time, it would kind of make things a bit more stilted… You want there to be camaraderie and for them to get on. I think anything that inhibits that is not great."* This distinction, between reviewing robotic actions versus monitoring human ones, reflects a careful boundary the team has negotiated over time. It preserves psychological safety while still enabling technical review.

The engineer agreed that review data can be valuable, but only if used appropriately: *"If it's transparent and used as a training metric, I personally don't see an issue with that."* He likened it to flight simulators in aviation or laparoscopic trainers in medicine, tools to support skill development and self-reflection. What both interviewees rejected, however, was using such data to measure or rank operator productivity *"If it becomes a metric of performance, how fast people operate a machine, then that's a risk,"* the engineer said, *"In fusion, it's better to do it correctly than to do it quickly."* Speed-based metrics may encourage risky behaviors or create unhealthy workplace pressures. In high-stakes, high-consequence environments like fusion reactors, accuracy and safety must remain the priority.

Trust in operator decision-making is essential. For instance, operators must feel empowered to stop an operation if needed, without fear of being second-guessed: *"You need to be able to have the confidence to hit an emergency-stop… and to know that you have the power to do so,"* the operator explained. This cultural commitment to human judgment is reinforced throughout training and team practice. Ethical system design, therefore, includes not only interface layout and camera placement, but also organizational structures that support autonomy, responsibility, and mutual respect.

As ITER comes online, HRI systems will face new challenges: larger scales, more radioactive environments, tighter schedules, and increasingly sophisticated data streams. Both experts acknowledged that the future will require further development of tools, interfaces, and operator training strategies. Yet both were also clear that the human operator must remain central to system performance and safety. As the engineer put it, *"It's better to build tools that support the operator than try to replace them."* Ethics in

HRI is not an add-on; it is a design constraint as real as radiation shielding or mechanical strength.

5 Discussion

The interviews revealed that HRI systems are not merely tools for safe manipulation but play a central role in the operational strategy of nuclear fusion decommissioning. As a highly complex, hazardous, and tightly regulated engineering environment, fusion infrastructure provides a distinctive context in which humans and machines must interact, learn, and adapt together. This discussion highlights three central insights emerging from the expert accounts: (A) HRI as empowerment rather than replacement, (B) the need for adaptable, human-centered systems, and (C) the importance of embedding ethics and transparency from the start.

5.1 Empowerment through Robotics

Contrary to narratives about automation displacing human workers, the experts in this study positioned robotics as an extension of human ability, allowing workers to operate in environments where direct intervention is impossible. *"If you want to deal with [fusion machines], you use robotics. You don't use people,"* said the engineer. This does not indicate a removal of human judgment, but rather a reconfiguration of how it is exercised. Operators are active decision-makers guiding machines with millimeter precision.

In this way, HRI shifts the locus of control from proximity-based action to cognition-based remote influence. The combination of telemanipulation and real-time feedback supports operators in performing tasks that would otherwise be inaccessible. As previously noted, the operator remarked, *"You move the robot in the air, but feel that tile... and place it in a bucket,"* a comment that captures the intimacy of this remote embodiment. Through HRI, humans are not removed from the loop, but repositioned within it, allowing risk to be managed while preserving control, responsibility, and expertise.

5.2 Human-Centered Design for Complexity

Operators do not work in isolation, nor are they interchangeable. Systems like MASCOT and the articulated booms require teams of up to five people, each trained in overlapping but distinct tasks. Echoing an earlier point, the operator noted, *"Sometimes if there is a lot of work to do, it will naturally fall to the people that fit those roles better,"* reinforcing the significance of matching roles to operator strengths.

Rather than treating the operator as a fixed role, HRI design at JET accounts for human variability, recognizing that each team member brings unique strengths and areas of expertise. This human variability is supported by standardized, cross-compatible interfaces, allowing operators to transition smoothly between different tools and platforms without needing to relearn controls. This consistency is a critical feature for intuitive and seamless human-robot collaboration in high-pressure environments, to effectively reduce cognitive load, as well as enhance trust and confidence in human-robot collaboration [35].

Multimodal feedback is used selectively. While visual information cues remain dominant, haptic and auditory signals are deliberately constrained. The decision to abandon unnecessary audio alerts in favor of intuitive color coding reflects a focus on cognitive ergonomics. As the operator observed, *"We're looking for the value of the feedback rather than the quantity"*. Prior HRI research suggests that appropriately designed multimodal feedback can enhance situation awareness and reduce perceptual error, rather than overwhelm operators [36,37].

This design philosophy extends to the training program, which includes technical drills, team simulations, and skill-based puzzles. It recognizes that nuclear environments are not just dangerous, they're unforgiving. Operators must be skilled, but also confident, coordinated, and adaptable. The training framework reflects this complexity by preparing teams holistically, not just mechanically.

5.3 Ethics of Monitoring and Metrics

Both interviewees raised critical concerns about the collection and use of performance data. The operator supported the use of equipment-side video recordings, viewing them as a helpful tool for self-reflection and improving efficiency. However, she was firmly opposed to constant surveillance within the control room, expressing concern that it could undermine team camaraderie and create a more tense, less collaborative working environment. The engineer shared this view, cautioning against using performance data as a productivity benchmark. He stressed that prioritizing speed could compromise safety and quality. Instead, he advocated for using performance metrics as a tool for skill development, provided that their use remains transparent and supportive rather than evaluative. These perspectives align with broader HRI literature, which emphasizes the importance of transparency, intent, and stakeholder involvement in ethical design [27]. HRI systems should collect data to support improvement, not surveillance. Empowering workers also means respecting their privacy and autonomy, especially in high-stress, high-skill environments.

The findings suggest that HRI in fusion decommissioning operates as a socio-technical safety mechanism rather than a purely technical control system. Teleoperation is most effective when it augments human judgment and preserves operator authority. Safe performance appears to depend on cognitively sustainable interface design and collective, continuous training. Ethical decisions around data use shape trust and operational quality. While grounded in fusion decommissioning, these insights resonate with challenges reported in other safety-critical teleoperation domains, including medical robotics, space operations, aviation, and hazardous industrial maintenance.

Table 1: Lessons learned from HRI in fusion decommissioning

Lesson Learned	Description	Broader Relevance
HRI as augmentation, not automation	Teleoperation systems extend human capability rather than replacing human judgment, preserving operator authority and accountability	Applicable to surgical robotics, space robotics, and UAV operations
Cognitive load must be actively managed	Selective multimodal feedback (prioritizing visual and haptic cues) outperforms information-rich but noisy interfaces	Relevant to any long-duration, high-stress teleoperation
Standardization supports flexibility	Consistent interfaces across platforms allow operators to switch roles and systems without retraining	Supports scalability in multi-robot and multi-team environments
Training as socio-technical process	Effective training integrates simulation, physical mock-ups, team coordination, and decision authority	Transferable to aviation, nuclear, offshore, and emergency-response domains
Ethical use of performance data builds trust	Performance data should support learning and reflection, not surveillance or productivity ranking	Critical for maintaining psychological safety in safety-critical work
Human authority as a safety feature	Operators must be empowered to stop operations without hesitation or penalty	Central to resilience engineering and accident prevention

6 Conclusion

This study provides qualitative insight into the multifaceted role of HRI in the decommissioning of nuclear fusion reactors. Through interviews with two experts at JET and ITER, the study highlights how teleoperation, haptics, VR-based planning, team-based workflows, and ethical interface design contribute to making robotic decommissioning feasible and manageable in practice.

The findings indicate that HRI supports fusion decommissioning in three important ways:

1. Reducing human exposure in environments involving radiation, tritium, and toxic materials.
2. Extending operational capability, enabling complex procedures to be performed remotely with high precision.
3. Supporting the development and transfer of expertise, through training, interface design, and responsible use of performance data.

These insights are grounded in current practice at JET, which represents the first full robotic decommissioning of a fusion facility. While the findings are necessarily limited in scope, they offer early evidence of how HRI considerations may inform future projects such as ITER. As fusion energy progresses toward large-scale deployment, responsible decommissioning will remain essential. In this context, HRI has the potential to play a critical supporting role in ensuring that fusion technologies are dismantled safely, transparently, and with sustained human oversight.

7 Limitations

This study has several limitations. First, it draws on interviews with two experts, providing depth of insight rather than breadth and limiting statistical generalizability. Second, the findings are grounded in the specific contexts of JET and ITER and may not fully represent other fusion or fission facilities operating under different regulatory or cultural conditions. Third, as fusion technologies and operational practices continue to evolve, some technical and ethical considerations discussed here may change over time. Finally, perspectives from additional stakeholders, such as regulators and broader operational teams, were not included. Despite these limitations, the study offers valuable initial insights into the human, technical, and ethical dimensions of HRI in fusion decommissioning and provides a foundation for future, more inclusive research.

Acknowledgments

This paper was based on the work performed in the JARVIS project sponsored by Horizon Europe (Project ID 101135708).

References

[1] ITER (2023). What is fusion? Retrieved from https://www.iter.org/fusion-energy/what-fusion

[2] Federici, G., Kemp, R., Ward, D., Bachmann, C., Franke, T., Gonzalez, S., ... & Wenninger, R. (2014). Overview of EU DEMO design and R&D activities. Fusion Engineering and Design, 89(7-8), 882-889. https://doi.org/10.1016/j.fusengdes.2014.01.070

[3] Barbarino, M. (2023). What is nuclear fusion? IAEA Department of Nuclear Sciences and Applications. Retrieved from https://www.iaea.org/newscenter/news/what-is-nuclear-fusion

[4] Toschi, R. (1997). Nuclear fusion, an energy source. Fusion engineering and design, 36(1), 1-8. https://doi.org/10.1016/S0920-3796(97)00007-0

[5] Smith, C. L., & Cowley, S. (2010). The path to fusion power. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 368, 1091-1108. https://doi.org/10.1098/rsta.2009.0216

[6] Romanelli, F., Barabaschi, P., Borba, D., Federici, G., Horton, L., Neu, R., ... & Zohm, H. (2012). Fusion Electricity: A roadmap to the realization of fusion energy. Retrieved from https://art.torvergata.it/bitstream/2108/132174/1/JG12.356-web.pdf

[7] International Atomic Energy Agency (2004). Planning, managing and organizing the decommissioning of nuclear facilities: lessons learned. IAEA-TECDOC-1394, Vienna. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/te_1394_web.pdf

[8] Gilbert, M. R., Zacharauskas, Ž., Almond, P., Scott-Mearns, N., Reynolds, S., & Lavrentiev, M. Y. (2024). Fusion waste requirements for tritium control: Perspectives and current research. Fusion Engineering and Design, 202, 114296.

[9] Liu, S., He, Y., Xie, H., Ge, Y., Lin, Y., Yao, Z., ... & Wang, B. (2022). A state-of-the-art review of radioactive decontamination technologies: Facing the upcoming wave of decommissioning and dismantling of nuclear facilities. Sustainability, 14(7), 4021. https://doi.org/10.1016/j.fusengdes.2024.114296

[10] Westwood, L. N., Gilbert, M. R., & Scott-Mearns, N. (2024). Fusion decommissioning and regulation (UK-STEP perspectives). Nuclear Fusion, 64(8), 085001. https://doi.org/10.1088/1741-4326/ad569f

[11] Suh, Y. A., Hornibrook, C., & Yim, M. S. (2018). Decisions on nuclear decommissioning strategies: Historical review. Progress in Nuclear Energy, 106, 34–43. https://doi.org/10.1016/j.pnucene.2018.02.001

[12] Park, K., Son, S., Oh, J., & Kim, S. (2022). Sustainable decommissioning strategies for nuclear power plants: A systematic literature review. Sustainability, 14(10), 5947. https://doi.org/10.3390/su14105947

[13] Goodrich, M. A., & Schultz, A. C. (2007). Human-Robot Interaction: A Survey, Foundations and Trends in Human-Computer Interaction, Vol 1.

[14] Sheridan, T. B. (2012). Human supervisory control. Handbook of human factors and ergonomics, 990-1015.

[15] Zhang, K., Plianos, A., Raimondi, L., Abe, F., Sugawara, Y., Caliskanelli, I., ... & Skilton, R. (2025). Towards safe, efficient long-reach manipulation in nuclear decommissioning: A case study on fuel debris retrieval at Fukushima Daiichi. Journal of Nuclear Science and Technology, 62(1), 1-16. https://doi.org/10.1080/00223131.2024.2386478

[16] Talha, M., Ghalamzan, E. A. M., Takahashi, C., Kuo, J., Ingamells, W., & Stolkin, R. (2016). Towards robotic decommissioning of legacy nuclear plant: Results of human-factors experiments with tele-robotic manipulation, and a discussion of challenges and approaches for decommissioning. In 2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR) (pp. 166-173). IEEE. https://doi.org/10.1109/SSRR.2016.7784294

[17] Vitanov, I., Farkhatdinov, I., Denoun, B., Palermo, F., Otaran, A., Brown, J., ... & Althoefer, K. (2021). A suite of robotic solutions for nuclear waste decommissioning. Robotics, 10(4), 112. https://doi.org/10.3390/robotics10040112

[18] Murphy, R. R., Tadokoro, S., & Kleiner, A. (2016). Disaster robotics. In Springer handbook of robotics (pp. 1577-1604). Cham Springer. https://doi.org/10.1007/978-3-319-32552-1_60

[19] Murphy, R. R. (2004). Trial by fire [rescue robots]. IEEE Robotics & Automation Magazine, 11(3), 50-61. https://doi.org/10.1109/MRA.2004.1337826

[20] Van der Meijden, O. A., & Schijven, M. P. (2009). The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. Surgical endoscopy, 23(6), 1180-1190. https://doi.org/10.1007/s00464-008-0298-x

[21] Okamura, A. M. (2009). Haptic feedback in robot-assisted minimally invasive surgery. Current opinion in urology, 19(1), 102-107. https://doi.org/10.1097/MOU.0b013e32831a478c

[22] Suchman, L. (2007). Human-Machine Reconfigurations: Plans and Situated Actions. Cambridge University Press.

[23] Seward, D. W., & Bakari, M. J. (2005). The use of robotics and automation in nuclear decommissioning. In 22nd International Symposium on Automation and Robotics in Construction ISARC, Ferrara, Italy.

[24] Marturi, N., Rastegarpanah, A., Takahashi, C., Adjigble, M., Stolkin, R., Zurek, S., ... & Bekiroglu, Y. (2016) Towards advanced robotic manipulation for nuclear decommissioning: A pilot study on tele-operation and autonomy. In 2016 International Conference on Robotics and Automation for Humanitarian Applications (RAHA) (pp. 1-8). IEEE. https://doi.org/10.1109/RAHA.2016.7931866

[25] Bird, B., Nancekievill, M., West, A., Hayman, J., Ballard, C., Jones, W., ... & Lennox, B. (2022). Vega—A small, low cost, ground robot for nuclear decommissioning. Journal of Field Robotics, 39(3), 232-245. https://doi.org/10.1002/rob.22048

[26] Yue, J., Tian, W., Wu, X., Liu, Z., Su, F., Gu, Q., & Jiang, C. (2025). A Path Planning Algorithm Considering the Feasibility Region of Nuclear Decommissioning Robots. Nuclear Science and Engineering, 1-13. https://doi.org/10.1080/00295639.2025.2509471

[27] Cryer, A., Sargent, A., Abe, F., Baniqued, P. D., Caliskanelli, I., Kivrak, H., ... & Skilton, R. (2023). Digital mock-ups for nuclear decommissioning: a survey on existing simulation tools for industry applications. Robotics and Automation Engineering Journal 5(4), 1-16. https://doi.org/10.19080/RAEJ.2023.05.555669

[28] Cardenas, J. J. G., Hei, X., & Tapus, A. (2024). Exploring cognitive load dynamics in human-machine interaction for teleoperation: A user-centric perspective on remote operation system design. In 2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 12204-12211). IEEE. https://doi.org/10.1109/IROS58592.2024.10802226

[29] Nick, A., Damm, N., Reiser, J. E., Baumann, M., & Deml, B. (2025). Understanding teleoperation: A human-centred framework for workplace design. Zeitschrift für Arbeitswissenschaft, 79(4), 581-593. https://doi.org/10.1007/s41449-025-00492-3

[30] Felt, U., Fouché, R., Miller, C. A., & Smith-Doerr, L. (Eds.). (2016). The handbook of science and technology studies. MIT Press.

[31] Bogner, A., Littig, B., & Menz, W. (Eds.). (2009). Interviewing experts. Springer.

[32] Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

[33] Clarke, V., & Braun, V. (2014). Thematic analysis. In Encyclopedia of critical psychology (pp. 1947-1952). Springer, New York, NY.

[34] Terry, G., Hayfield, N., Clarke, V., & Braun, V. (2017). Thematic analysis. The SAGE handbook of qualitative research in psychology, 2(17-37), 25.

[35] Kalatzis, A., Rahman, S., Girishan Prabhu, V., Stanley, L., & Wittie, M. (2023). A multimodal approach to investigate the role of cognitive workload and user interfaces in human-robot collaboration. In Proceedings of the 25th International Conference on Multimodal Interaction (pp. 5-14). https://doi.org/10.1145/3577190.361411

[36] McCrudden, M. T., & Rapp, D. N. (2017). How visual displays affect cognitive processing. Educational Psychology Review, 29(3), 623-639. https://doi.org/10.1007/s10648-015-9342-2

[37] Zheng, C., Wang, K., Gao, S., Yu, Y., Wang, Z., & Tang, Y. (2025). Design of multi-modal feedback channel of human–robot cognitive interface for teleoperation in manufacturing. Journal of Intelligent Manufacturing, 36(6), 4283-4303. https://doi.org/10.1007/s10845-024-02451-x



https://dspace.org/

(Em)Powering the end of power: HRI for safe nuclear decommissioning

Oostveen, Anne-Marie; Zhang, Jingyi; Fletcher, Sarah

2026-03-16
Association for Computing Machinery (ACM)
https://doi.org/10.1145/3757279.3788661
Oostveen A-M, Zhang JE, Fletcher S. (2026) (Em)Powering the end of power: HRI for safe nuclear decommissioning. In: The Proceedings of the 21st ACM/IEEE International Conference on Human-Robot Interaction. HRI '26: 21st ACM/IEEE International Conference on Human-Robot Interaction, 16-19 March 2026, Edinburgh, UK

Downloaded from a DSpace repository. https://dspace.org/