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Review

Review and down-selection of NDE technologies suitable for ITER cooling water system remote weld inspections

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ABSTRACT

ITER In-Vessel Components (IVCs) will have limited lifetimes and need to be maintained and/or replaced during the operational life of ITER. IVCs are attached to the plant cooling water system via pipework to enable active cooling of the components during plasma operations. When maintenance is required, Remote Handling Systems (RHS) will be used to remotely cut the connecting pipework as the environmental and space constraints are not suitable for humans. The components will then be transferred into the Hot-Cell Facility where they can be inspected, refurbished or disposed. During reinstallation, remote rewelding of the pipes will be required. The integrity of the remotely welded joints must be demonstrated remotely by the means of Non-Destructive Evaluation (NDE) to ensure the weld quality requirements are met. Establishment of a weld acceptance process that can be applied to all remote welds across ITER is therefore required. In this study, applicable NDE technologies for ITER remote weld inspection are reviewed. Scoring criteria is defined and Eddy Current Testing (ECT) and Phased Array Ultrasonic Testing (PAUT) were selected as the most suitable technologies for the defined use cases.

1. Introduction

The accessibility of cooling pipe systems during maintenance on ITER will be challenging as most could be either accessed in-bore or ex-bore due to space constraints.

When maintenance on components connected to theses cooling pipe systems are required, Remote Handling Systems (RHS) will be used to remotely cut all the associated embedded pipes and the component transferred into the Hot-Cell Facility where they can be inspected, refurbished or disposed. During reinstallation, remote rewelding of the pipes will be required when replacing the components after repair. The integrity of new remotely welded joints must be demonstrated by means of NDE outcomes in order to ensure it meets the requirements of the designated design code and/or standard. The applicable welding standard for the pipes is EN 5817 level B. Volumetric inspection of the pipe welds is mandated and the chosen volumetric inspection technology must be capable of identifying weld defects with the level of precision mandated by standards.

The most common weld volumetric inspection technologies are radiographic and ultrasonic [1]. However, these technologies may not be suitable inspection of remote weld joints on fusion reactors such as ITER. The presence of gamma rays would make radiographic not applicable. Also, conventional ultrasonic testing is typical recommended for inspection on pipes with thickness above 5 mm. At the time of writing this article ITER was considering pipe thickness below 5 mm as there will be easy to cut and weld remotely. Hence, alternative NDE technologies shall be considered.

In 2013, Institut de Soudures (I.S.) reported on assessing the defect detection capability of four different NDE methods: Ultrasonic testing (UT), Electro Magnetic Acoustic Transducer (EMAT), Eddy Current Testing (ECT) and Alternating Current Field Measurement (ACFM) for the validation of non-destructive testing for blanket cooling pipe welds [6]. Mock-ups for the assessment were manufactured using Tungsten Inert Gas (TIG) without filler metal in a single run. The main expected defects were lack of fusion perpendicular to surfaces or lack of penetration. Results from their assessment shows ECT had a greater potential to be used for in-vessel components welds inspection compared to other technologies.

The United Kingdom Atomic Energy Authority (UKAEA) [7] also conducted a series of trials intended as an exploratory investigation into

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the performance of EMAT and PAUT in 2018. To compare the two candidate technologies, five welded samples with defects were produced. EMAT was selected as the most viable candidate technology for the Divertor Remote Handling System (DRHS) pipe maintenance tooling. However, further development was recommended due to the limitations identified and the acceptable defects being unknown.

A Plus Point eddy current probe has been used in a previous study by the Japan Domestic Agency - National Institutes for Quantum and Radiological Science and Technology (JADA-QST) in 2018 [8] because it is less susceptible to the noise coming from the non-uniformity of weld bead as compared to eddy current array probes. The aim of the study was to improve the defect detectability by Eddy Current Testing as well as evaluate the feasibility of ECT to the welded part of the blanket cooling pipe. However, other studies have also exposed that conventional eddy current testing may not be reliable for the detection of sub-surface defects and they have recommended considering high frequency probes [9].

This study focuses on identifying an NDE technology suitable for inspecting the integrity of remotely welded joint on ITER, taking into consideration factors such as the technology's applicability, RH compatibility, and environmental tolerances.

2. Methodology

2.1. Case studies

A large variety of thin walled (≤3 mm) austenitic stainless-steel cooling water system pipes exist within ITER. All pipes are envisaged to be welded via autogenous TIG welding methods. Unfortunately, that is where the commonality ends and significant variance between parameters such as geometry, grade of steel, alignment, cutting and welding methods, their environmental constraints as well as their access for deployment and inspection exist from one application to another. To rationalise the problem, five use cases were selected for this study. The definition and description of the use cases are defined in Table 1 and computer models (for use cases 1 and 5) illustrating the weld location are in Fig. 1.

2.2. Inspection constraints for remote inspection of ITER

There are many challenges that need to be overcome by the selected technology for reliable volumetric inspection of the pipe welds. Some of these challenges are listed below:

- *Material*

According to ITER material design database [2], pipe welds will be made of 316L-1.4404 or 316LN-IG forging. These materials are employed for their good mechanical properties at elevated temperatures, excellent corrosion resistance, ease of fabrication with good weldability and fracture toughness. However, due to their grain size, high scattering could occur which may lead to attenuation when using some NDE technologies. This will result in reduction in the signal to noise ratio, hence poor sensitivity of defect detection [3].

- *Geometry and surface finish*

Surface roughness and flatness also has potential of affecting the detection capability of some inspection technology [4]. The welds cannot be smoothed or flat before the inspection is conducted; thus, the roughness and flatness of the weld beads might also affect the performance of the selected NDE.

- *Small Thickness Pipe Inspection*

The selected technology should have the capacity of inspecting pipes with thickness below 3 mm. This would be challenging for technologies that have dead zones issues. This is a region beneath a transducer in which no useful inspection can take place. A dead zone is inherent in all ultrasonic equipment.

- *Environmental Constraints*

The robustness of an NDE technology to withstand high gamma radiation exposure and temperature i.e, 730 Gy/hr and 20 to 80 deg C respectively would be useful.

- *Space Constraints*

It is crucial to consider the limited accessibility of the welded pipes. Table 1 provides valuable information regarding the preferred inspection methods for different scenarios. In cases such as use case 1 where in-bore inspection is preferred, the inner diameter of the pipes is 42.7 mm. Therefore, the measuring head used for these inspections should have a diameter of no more than 40 mm, ensuring it can fit into the narrow space. It is important to note that only one side of the pipe can be accessed for inspection, either in-bore or ex-bore. Consequently, inspection techniques like radiography, which require access to both sides of the pipe, would not be suitable. Moreover, the accessibility of the welds varies depending on the specific case being considered. However, it is essential to select a technology capable of performing both in-bore and ex-bore inspections. This technology should be versatile enough to accommodate pipes with different diameters, such as the ones in use case 3, which have a diameter of 213 mm.

- *Allowable Defect Size*

The selected technology should not only be able to detect the maximum permissible defect but should be able to detect the smaller size defect. Using existing procedures such as BS 7910, EDF R6, RCC-MR and RSE-M codes a defect tolerance assessment can be conducted on series of ITER pipe weld to compute the theoretical end of life limiting defect size. The selected technology should have the capability to detect the start of life limiting defects. The type of defect typically in a weld could be cracks, tungsten inclusion, lack of fusion, sagging or crater crack. For the purpose of this study, the minimum size of a defect that should be detectable by the NDE technology is $3 \times 0.5 \times 0.25$ mm^3.

- *Sensitivity of NDE for Remote Handling Inspection*

The selected technology should be remote handling compatible, i.e. the selected technology should be easily automated and deployed using a remote handling system.

Table 1
Definition of use cases selection and referred to in the study.

Use Case	Component	Candidate Designation	Outer diameter (mm)	Inner diameter (mm)	Access (In/Ex bore)	Rad.exposure (Gy/hr)
1	Blanket	FW to SB cooling pipe welding	48.72	42.72	In bore	<730
2	Blanket	FW to SB cooling pipe cap welding	54.00	42.70	In bore	<730
3	Diagnostic Shield Module	DN25 SCH 10 CWS	33.40	27.86	Ex bore	<1
4	Neutral Beam	DN200 SCH 10 CWS	219.10	213.10	Ex bore	<1
5	Divertor	DN65 SCH 10 s	70.00	64.00	Ex bore	<300

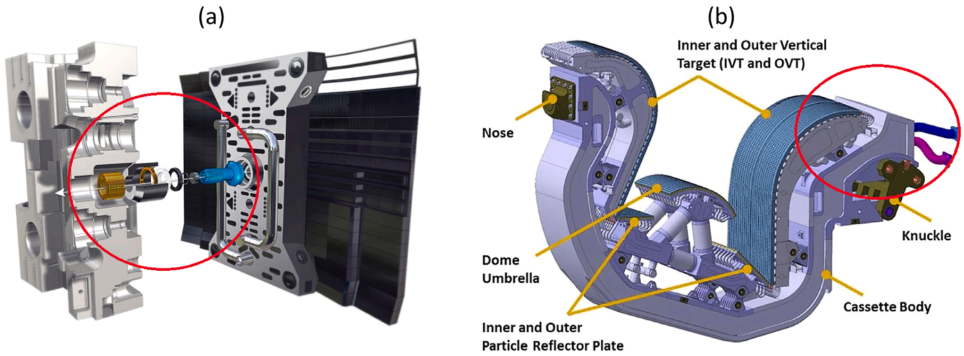

Fig. 1. Computer models of the use cases under investigation in this study. Red circles highlight weld location and (a) Use case 1 -Blanket: First Wall to Shielding Block weld on forged machined pipes, (b) Use case 5 - Divertor: First Wall to Shielding Block cooling pipe cap weld.

2.3. *Review and down-selection approach*

Two approaches were utilized for the identification of the suitable NDE technology for remote inspection of pipe welds. These two approaches were considered to ensure the selection was not only based on literature review but also input of NDE industrial experts as well.

2.3.1. *Review of NDE Suitable NDE technology*

Due to the nature of the ITER project, NDE assessments have been conducted before. Hence, it is important to review the most relevant reports that have been produced. Technologies that have been considered in earlier ITER NDE studies were rated based on their ability to detect defects in a mock-up. Table A.1 shows the scoring criteria for technologies that have been considered in previous ITER NDE studies.

It is worth mentioning that due to the scheduled operation date of ITER, the technologies reviewed were considered based on their readiness level. It is also expedient to state that since the materials used for this study are austenitic stainless steel 1.4404 (316L) and 316LN-IG forging; technologies such as Terahertz and Microwave NDE which have good penetration in non-metallic materials and could be deployed for volumetric inspection will not be reviewed.

Also, further review of these technologies and their success in other industries were carried out. For comparison of various NDE technologies, all technologies that are reviewed were rated using a defined scoring criteria and weighting agreed upon by the authors presented in Table A.2.

2.3.2. *Survey*

An effective way to engage with experts in the NDE industry as well as capture an unbiased opinion of NDE experts for the down selection process of NDE technology suitable for the inspection of remote pipe welds was considered. This involved the adaptation of a twofold approach in engaging with a well-established NDE Society (RCNDE). The first was the presentation of the requirement and the nature of the problem as well as any crucial factors that might affect the performance of NDE technology to the experts followed by deployment of a systematic approach to capture feedback on the performance of various technologies for experts under difference scenarios.

The UK Research Centre in Non-Destructive Evaluation (RCNDE) is a collaboration between industry and academia to coordinate research into NDE and structural health monitoring (SHM) technologies, and to ensure research topics are relevant to the medium to longer-term needs of industry. The Centre’s vision is to see NDE and SHM transform into a fully integrated part of the engineering life cycle and the aim is to progressively link up with other disciplines, particularly structural integrity, materials science and engineering design. Members of RCNDE span across multiple industry sectors (e.g. nuclear, aerospace, oil & gas, high-value manufacturing, defense, transport) and geographies (UK, EU, North & South America and Japan) [5].

The total number of participants was 36. Due to General Data Protection Regulation (GDPR), details of the attendees will not be provided in the article. However, the authors could confirm a fair spread of participants across various industries, academics and research centers.

The survey questionnaires were grouped under following main headings as outlined below and based on the responses; the authors agreed on the scoring criteria (Table A.3 – A.8) for each group.

a Material, geometry and small thickness pipe inspection
b Environmental constraints and allowable defect size
c Robustness and sensitivity of NDE for remote handling inspection

Since all the criteria from Table A.3 – A.8 do not have the same impact regarding successfully deploying the selected technology for NDE inspection on ITER pipe welds, the following weighted scores in Table 2 are allocated to all the criteria, as agreed upon by the authors upon discussion with key stakeholders such as ITER Remote Handling System Engineers and NDE Manufacturers.

3. Results – technology assessment

3.1. *Review of NDE suitable NDE technology*

3.1.1. *Phased array ultrasonic testing (PAUT)*

Phased Array UT uses a series of piezoelectric elements (typically from 16 to 256) within a single probe, allowing beam angling, sweeping, and focusing through constructive and destructive wave interference. Although typically applied to thicker walled joints (typically > 6 mm according to ISO 13588), some success has been achieved in small thickness pipes.

The qualification of welds with thickness below 5 mm has been reviewed recently. This has been demonstrated and standardized as ISO 20601:2018 [10] which specifies the application of PAUT for the semi- or fully-automated ultrasonic testing of fusion-welded joints in steel parts with thickness value between 3.2 mm and 8.0 mm. At a recent symposium organized by KINT [11], the Dutch Quality Surveillance and Non-Destructive Testing Society presented results obtained from various theoretical and experimental work done in order to define the

Table 2
Weighted scoring of criteria for survey.

Criteria	Weighted score
Material	20%
Geometry	12%
Small thickness pipe	16%
Environmental constraints	14%
Detectability of allowable defects	12%
RH compatibility	17%
Sensitivity	9%

acceptance levels when using ISO 20601:2018.

The applicability of PAUT for volumetric inspection has also been assessed on austenitic stainless steel with fabricated artificial defects of different volumetric dimensions [12]. Defects were rectangular grooves with dimensions (depth x width x height) mm of 25 × 1 × 4, 20 × 0.5 × 4, and 50 × 0.2 × 4.

The following is a summary of PAUT after the review.

- PAUT has been used for inspection of both fission and fusion component.
- PAUT has been used for pipe weld inspection
- PAUT dead zone region could be reduced, unlike conventional Piezoelectric UT.
- PAUT utilizes similar elements just as Piezoelectric UT, hence, would require radiation hardened
- PAUT has good repeatability, and it is good for monitoring.

Upon the review carried out by the authors, PAUT was rated 4.35 out of 5 for its environmental tolerance, 2 out of 3 for its detectability of defect in fusion relevant mock-ups and 4.05 for its applicability.

3.1.2. *Electro-magnetic acoustic transducer (EMAT)*

EMAT combines a magnetic field typically created by a permanent magnet and an alternating eddy current induced by an electrical coil to generate Lorentz forces within the material being examined. These Lorentz forces create mechanical strains within the material, which lead to the generation of mechanical vibration – ultrasound. As the signal is generated within the material itself, there is therefore no requirement for a couplant when inspecting with EMAT.

Typically, the use of permanent magnets in EMATs presents challenges in terms of mobility. This is due to the inherent nature of permanent magnets, which have a strong attraction to iron particles and exhibit limited movement on ferromagnetic materials like steel pipes. As a result, the presence of permanent magnets in EMATs can impede their ability to effectively navigate and inspect these materials in real-time scenarios.

This problem can be solved by the pulsed electromagnet EMAT. A pulsed electromagnet using core solenoid instead of the permanent magnets. There are mainly two kinds of core solenoid structures for pulsed electromagnet: the iron core solenoid (ICS) structure and the air core solenoid (ACS) structure. Comparing the two, the ICS structure can produce stronger magnetic field with the same charging current and the attenuation of magnetic flux density is slower [13].

Magnetic field produced by core solenoids are usually lower than that produced from permanent magnets. This has a great impact on the noise-to-signal ratio during inspection, hence affecting detectability of small sub-surface defects. An approach to increase the magnetic field for pulsed EMAT is by using super conductive coils.

Research that confirms defects with dimensions of 1–11 mm length and 0.5–2 mm depth can be detected when using EMAT has been conducted [14] as well as studies that requires retrofitting of EMAT on a robotic inspection manipulator for detection of defects in the first wall of Tokamak fusion reactors [15] has been conducted, confirming its applicability for volumetric inspection in harsh environments.

The environmental tolerance of EMAT was investigated previously for ITER weld inspection as detailed in the 1999 JAERI report [16]. The report provides useful information on the radiation tolerance of the EMAT inspection technique: a 700 kHz probe emitting SH ultrasonic waves was subjected to a dose rate of 10 kGy/h increased to 10 MGy/h with no significant degradation. The cumulative ITER dose of 600 KGy is well within the operating limits of this equipment. Primarily the radiation hardness is derived from the use of radiation hard components namely a SmCo permanent magnet and Polyamide based coil.

The following is a summary of EMAT after the review.

- EMAT; unlike PAUT and other Piezoelectric based technology, will not be affected by angling of the probe during inspection nor will it be affected by weld beads and debris.
- Previous assessments by JAERI confirms EMAT's performance in high radiation and will not deteriorate during operation.
- This technology has been used for the inspection of pipe welds.

Upon the review carried out by the authors, EMAT will be rated 5 out of 5 for its environmental tolerance, 2 out of 3 for its detectability of defect in fusion relevant mock-ups and 4.25 for its applicability.

3.1.3. *Time of flight diffraction (ToFD) UT*

Time of Flight Diffraction UT (ToFD UT) uses two transducers; a transmitter and receiver positioned in a pitch-catch arrangement on opposite sides of the weld. Emitted ultrasound diffracts around defects, causing variation in the received signal. Signal modification due to diffraction is less affected by defect orientation than that seen with the pulse-echo technique, so defect sizing can be performed more accurately with ToFD.

ToFD ultrasonic inspection suffers from two blind spots: near surface defects are masked by the lateral wave, and root misalignment is masked by the back wall reflection. However careful probe specification and wave modelling can help optimise the inspection to reduce these effects [17].

Merging of the various wave types (lateral, back wall, and defect induced diffractions) in very thin-walled samples can make defect identification very difficult. ASME permits use of ToFD for inspection of thicknesses greater than 12 mm.

Longitudinal waves diffracting around a defect also generate shear waves as well as being diffracted themselves. These shear waves travel at half the speed of the longitudinal waves, and so arrive later at the receiver. This longer duration allows more accurate defect sizing, and helps avoid the masking effect of other reflections, such as from the back wall, and lateral wave interference, improving near surface defect identification and sizing. This technique is known as Shear-ToFD and has been shown to improve defect identification and sizing capabilities for thin walled materials [18].

This technique is affected by beam spread, mode conversion, and attenuation which does not permit the detection of defects several skips away. In this application the attenuation associated with the material is likely to be prohibitive, especially when using high frequency waves, which are required to resolve the defect sizes specified in the requirements. This problem can be overcome by scanning in one direction and then the other however this is only likely to highlight the presence of a defect and not the location. Lack of fusion and lack of penetration may create defects which sit in the plane of the weld, and as such might not show up well on ultrasonic scanning techniques which propagate waves in line with the weld path.

TOFD is having the recognition from international bodies. The British Standard Institute has issued a TOFD standard BS: 16828-2014, which provides guidance on the application of TOFD technique for the detection, location and sizing of flaws in materials. There is a European TOFD standard draft ENV 583-6 Non-destructive testing - Ultrasonic examination part 6 - Time of Flight diffraction technique as a method for defect detection and sizing.

Based upon the information available, the following were deduced.

- ToFD has been used for pipe weld inspections
- ToFD comprise of two Piezoelectric UT probes or PAUT probes, hence it is bond to face all challenges associated with them such as dead zone in cases a piezoelectric probe is used.

Upon the review carried out by the authors, ToFD was rated 4.35 out of 5 for its environmental tolerance, 0 out of 3 for its detectability of defect in fusion relevant mock-ups and 2.7 for its applicability, due to alignment issues i.e. more complex mechanical arrangement.

3.1.4. Eddy current array

Eddy current testing can detect defects in materials with thickness less than 5 mm [19]. Further experiments conducted on stainless steel test samples with thickness that varied from 1 mm to 5 mm to represent the pipelines in the nuclear power plants confirms the potential to use ECT for detecting defects in small-thickness pipes [20].

Additionally, this technique has been successfully used to inspect pressurised water reactors [21]. Research has also been conducted in the development of eddy current probes to detect sub-millimeter defects with any orientation on the inner surface of ITER pipes [22] as well as an applicability assessment of the technology for a 3 mm thick ITER blanket cooling pipes [23] with both methods being successful. However, further tests would be required to determine the impact of magnetic fields on the performance of the probes.

ECT is known for its limit in depth of penetration. The depth at which only 37% of the surface eddy current density is often used as a metric of penetration. The inspection depth can be varied by altering the frequency of the probe. Higher frequencies increase near surface resolution and lower frequencies increase penetration depth. Addition of a supplementary magnetic field in the sensing region (for example through inclusion of a permanent magnet [24]) can improve signal to noise ratio. Eddy current testing is dependent on close contact between the probe and the test surface, however no couplant is required. For effective eddy current testing of welds, it should be noted that local adverse weld forms, excessive weld spatter, scale, rust and loose paint can influence sensitivity by separating the probe from the test object thereby inducing noisy responses.

Inspecting large surface areas using a single-coil probe (ECT) is extremely impractical as the process would be time consuming and the probability for missed flaws is high . Eddy current array (ECA) technology remedies these issues. Eddy Current Array (ECA) is an advanced form of Eddy Current Testing (ECT) that incorporates an array of individual coils or sensors. These coils are arranged in a specific pattern and can be excited individually or simultaneously, allowing for enhanced inspection capabilities. ECA provides more detailed and comprehensive inspection results compared to traditional ECT, as it enables faster scanning over larger areas and can detect and characterize defects with higher resolution. Furthermore, the capacity of ECA to inspect large surfaces makes it an advantageous replacement for traditional techniques such as magnetic particle or liquid penetrant inspection.

Based upon the publicly available literature, the following were deduced.

- ECT has been used for pipe inspection
- ECT has been used for NDE on both Nuclear Fusion and Fission components
- ECT has been used to access welds remotely in challenging environments

Upon the review carried out by the authors, ECA was rated 5 out of 5 for its environmental tolerance, 3 out of 3 for its detectability of defect in fusion a mock-up and 4.3 for its applicability

3.2. Survey

3.2.1. Phased array ultrasonic testing (PAUT)

3.2.1.1. Material, geometry and small thickness pipe inspection. Based on the information captured from the survey, PAUT has the capability of detecting defects in components made of stainless steel as well as stainless steel forging. However, the detection size depends on parameters such as grain size. Challenges that are likely to be faced maybe the high level of material backscatter and beam steering due to heterogeneity.

This could be resolved by using high frequency probes. Hence, PAUT is rated 4 out of 4 which is equivalent to 4 points for its capability to detect defects in the selected material.

Regarding using off-the-shelf PAUT equipment for inspection of the selected cases, the geometries of the selected cases might require case-specific customised probes. This might require R&D planning for the selected cases. Hence, PAUT is rated 1 out of 4 which is equivalent to 0.96 points for its capability to overcome challenges posed by the geometry of the selected cases.

Based on the survey, the capability for PAUT to detect defects in small thickness pipes was rated 2 out of 4 which is equivalent to 1.92 points. The survey exposed PAUT could easily detect defect in pipes with thickness > 5 mm and might struggled with thickness < 4 mm. The selected cases have wall thickness ranging from 2.77 mm to 3 mm. Some of the participants also highlighted that a thickness range between 2 – 5 mm is within the abilities for this technique, however, R&D will be required as defect size could play a keen role in the success of this technology.

3.2.1.2. Environmental constraints and allowable defect size. According to the feedback obtained from the survey, since PAUT is optical based, environmental constraints such as the level of radiation and magnetic fields stated in this project will not affect the performance of this technology. Even though the magnetic field might affect the polarisation of light which may be used for ultrasonic detection purposes, this might be resolved by adjustment. It was also mentioned that since this technology is regularly used for nuclear fission inspection, it has a high potential of surviving in the stated environment in Table 1. PAUT is therefore rated 4 out of 4 which is equivalent to 2.8 points under its ability to withstand the stated environmental constraints.

From the survey, the resolution of PAUT is most likely to be in the micrometer range. That is, it could easily detect defects ~ 1 mm. However, factors such as wall thickness, orientation of defect and the level of grain noise will also affect the resolution of the technology hence altering the smallest defects it may detect. PAUT was rated 3 out of 4, which is equivalent to 1.92 points for its detectability of the expected defects.

3.2.1.3. Robustness and sensitivity of NDE for remote handling inspection. PAUT was rated 4 out 4 which is equivalent to 3.4 points for its RH compatibility. This is because similar application of PAUT has been used in other sectors which includes the nuclear fission industry. However, it is sensitive to debris and weld beads. The preferred scanning surface when using PAUT is smooth finish. The sensitivity of this technology was, therefore, rated 2 out of 4 which is equivalent to 1.8 points.

3.2.2. Electro-magnetic acoustic transducer (EMAT)

3.2.2.1. Material, geometry and small thickness pipe inspection. Based on the information captured from the survey, EMAT has the capability of detecting defects in components made of stainless steel as well as stainless steel forging but would have been more successful if the components were made of Aluminium and Ferritic Steels. Even though stainless steel is more difficult to test with EMAT, it can be done with the correct equipment. Hence, EMAT is scored 4 out of 4 which is equivalent to 4 points for its capability to detect defect in the selected material.

Participants of the survey warranted that the geometries of the selected cases might impact on the performances on EMAT. Customized probes might be required as the size of off-the-shell equipment may be a limitation of the used cases. Hence, EMAT is rated 1 out of 4 which is equivalent to 0.96 points for its capability to overcome challenges posed by the geometry of the selected cases.

EMAT is rated 1 out of 4 for its capability to measure defects in pipes with thickness within the defined range which is equivalent to 1.28 points. This is due to a trade-off between defect size, frequency, signal to noise ratio and the pipe thickness.

3.2.2.2. Environmental constraints and allowable defect size. Participants of the survey confirmed that the magnetic field could affect part of the excitation mechanism of the EMAT system hence more R&D is required to control the influence of the external magnetic field i.e. most EMATs are constructed using polymers as permanent magnets which might need to be replaced. Also, radiation could be an issue for EMAT. Based on the information gathered during the survey, EMAT is scored 2 out of 4 which is equivalent to 1.68 points for its environmental resistance.

EMAT is rated 2 out of 4 under the possibility of detecting the allowable defects which is equivalent to 1.44 points. This was based on comments such as the following which was captured during the survey.

"The defects that were presented were pretty small, this would mean a small high frequency setup and it would also mean that the weld bead irregularities might result in spurious indications."

3.2.2.3. Robustness and sensitivity of NDE for remote handling inspection. EMAT is said to be very tolerant to misalignment and since it does not require any form of couplant, the participants of the survey scored it 4 out of 4 for its RH compatibility which is equivalent to 3.4 points.

Also, even though weld bead is a big issue for this technology, reducing the debris would make EMAT stand a much better chance. Alternatively, ensuring the probe has good contact with the surface might mitigate this challenge. Hence, EMAT is scored 2 out of 4 which is equivalent to 1.8 points for its sensitivity.

3.2.3. Time of flight diffraction (ToFD) UT

3.2.3.1. Material, geometry and small thickness pipe inspection. ToFD is rated 4 out of 4 which is equivalent to 4 points for its capability to detect defect in the selected materials just as PAUT.

However, it is rated 0 out of 4 for its capability to overcome challenges posed by the geometry of the selected cases. This is because, two case specific PAUT probes might be required as well as a complex approach to align them on complex geometries.

ToFD might face great challenge with in-bore inspections of pipes as well as pipes with thickness below 6 mm. Hence it is scored 1 out of 4 which is equivalent to 1.28 points for its capability to be used for small pipe inspection.

3.2.3.2. Environmental constraints and allowable defect size. ToFD is rated as 4 out of 4 which is equivalent to 2.8 points under its ability to withstand the stated environmental constraints just as PAUT.

However, ToFD is expected to have a better resolution when compared to PAUT, hence it is rated at 3 out of 4 which is equivalent to 1.92 points for its ability to detect the allowable defect

3.2.3.3. Robustness and sensitivity of NDE for remote handling inspection. ToFD is very sensitive to weld bead as well as debris on surfaces during inspection. However, it could easily be deployed on a robotic handling system for inspections. Hence it is scored 0 out of 4 which is equivalent to 0 points for its sensitivity and 4 out of 4 which is equivalent to 3.4 points for its remote handling compatibility.

3.2.4. Eddy current array

3.2.4.1. Material, geometry and small thickness pipe inspection. Based on the survey, ECA has the capability to detect flaw in the selected material. However, there is also a high false indication rate especially with flaw acceptance criteria of ~ 0.5 mm. Hence, ECA is rated 3 out of 4 for its capability to detect flaw in the selected materials which is equivalent to 3.2 points.

ECA is rated 2 out of 4 which is equivalent to 1.44 points for its capability to overcome challenges posed by the geometry of the selected used cases. The outcome of the survey confirmed that the inspection could be designed to take care of the geometrical complexities of the component.

ECA is rated 4 out of 4 which is equivalent to 3.2 points for its capability to detect defects in small pipe thickness i.e. 2 mm – 4 mm.

3.2.4.2. Environmental constraints and allowable defect size. According to the outcome from the survey conducted, ECA will be affected by the environmental constraints presented during the Table 1 and might require R&D works which might include the use of non-silicon hall sensors such as Quantum Well Hall Sensors. This might provide better performance due to higher sensitivity, radiation hardness as well as wider operating range. ECA was rated 3 out of 4 which is equivalent to 2.24 points for its ability to withstand the stated environmental constraints.

It was however rated 4 out of 4 for its capability to detect the allowable defects which is equivalent to 2.4 points. One participant commented that, ECA is more than capable of detecting crack defects < 1 mm.

3.2.4.3. Robustness and sensitivity of NDE for remote handling inspection. Multiple approaches were recommended to overcome the impact of welded surfaces on the performance of ECT from the survey. Some of which includes, the use of low frequencies as they allow more immunity to surface conditions and debris. Hence ECA is scored 3 out of 4 for its sensitivity which is equivalent to 1.44 points.

It is also scored 3 out of 4 for its RH compatibility which is equivalent to 2.72 points. From the outcome of the survey, only few modifications might be done in order to ensure it performance is not compromised.

4. Discussion – down-selection of technology

From Table 3, it could be deduced that ECA had the highest scores. Based on research conducted by Japan Atomic Energy Research Institute (JAERI), its resistance to the expected environmental constraints and its applicability has been proven. Also, from the survey, ECA appears to be the appropriate technology suitable for small pipe thickness inspection as well as having the potential to detect defects < 1 mm.

The ability of ECA to detect wider range of planer defects in stainless steel pipe welds without the thickness of the pipe becoming a challenge makes it the preferred candidate over other technologies. Its remote handling compatibility as well as high tolerance to environmental constraints such as temperature and radiation establish its suitability for inspection on ITER. Modification of ECA probes to best fit its application is also a well-established concept in the NDE industry, that option allows various approach for increasing its performances. Probe shape and

Table 3
Summary of scoring of criteria for literature review and survey.

		PAUT	EMAT	ToFD	ECA
Literature Review	Detectability of defect in fusion relevant mock-ups	2.00	2.00	0.00	3.00
	Environmental tolerances	4.35	5.00	4.35	5.00
	Applicability	4.05	4.25	2.70	4.30
Survey	Material	4.00	4.00	4.00	3.20
	Geometry	0.96	0.96	0.00	1.44
	Small thickness pipe inspection	1.92	1.28	1.28	3.20
	Environmental constraints	2.80	1.68	2.80	2.24
	Detectability of allowable defects	1.92	1.44	1.92	2.40
	RH Compatibility	3.40	3.40	3.40	1.44
	Sensitivity	1.80	1.80	0.00	2.72
	Total	**27.20**	**25.81**	**20.45**	**28.94**

frequency are examples of factors that can easily be varied to improve the performances of ECA. However, difficulties in detecting defects in the backside of the pipe could be a challenge likely to be faced by this technology. Also, further R&D is strongly suggested to establish its compatibility with magnetic field and the subsequent effect that it has on the signal to noise ratio.

Either PAUT or EMAT seems to be suitable to be considered as a complementary technology to ECA for inspection of the usecases. This is because both could more easily measure defects close to the backwall of samples, which is the many challenges of ECA. Also, both technologies would face dead zone challenges which can easily be resolved by using the appropriate wedge during the inspection. Dead zones issues mainly affect the ability of the technology to detect surface and sub-surface defects which is not a challenge for ECA.

PAUT is preferred as the complementary technology to ECA not because it had the second highest score in Table 12 but also it stands a higher chance to withstand environmental constraints such as magnetic fields and radiations. The consideration of using dry couplants for inspection with PAUT increases its applicability on ITER pipes. PAUT is capable for inspecting defects in stainless steels pipe welds as well as easy to embed in a remote handling system. PAUT has the ability to detect internal defects as well as backside defects. However, further R&D is strongly recommended to establish its compatibility with magnetic field and the subsequent effect that it has on the signal to noise ratio. Also, R&D is highly suggested to investigate into remote compatible cleaning procedure as there is a likelihood that the couplant if used would require post-inspection cleaning.

Based on the recommended technologies from the survey, long-range UT technologies such as guided wave could be considered. However, most off the shelf guided wave UT equipment are not remote handling compatible of the described use cases. They are ideally used for ex-bore applications for pipes with outer diameter ranging between 2 to 48 inches. Considering this technology for our intended application would require a series of feasibility assessments, research and development activities.

5. Conclusions

The geometrical situation and environmental constraints of the cases considered in this paper require unique approaches for inspection. Also, a single NDE technology might not be able to detect different types of defects in the same weld. A combination of different technologies to evaluate defects increases the reliability of the results. In some of the cases outlined in Table 1, the two selected NDE technologies are recommended to be used together as complementary technologies.

In this paper, two technologies have been selected for volumetric defects inspection of re-weld pipes within ITER. This decision was derived though reviewing both publicly available literature as well as previous NDE projects on ITER. To ensure that the state-of-the-art capabilities of potential NDE technologies are captured during the review, a twofold approach was adapted to involve experts with industrial experience in various NDE technologies in this process.

Technologies were scored under various criteria such as applicability, RH compatibility, environmental tolerances amongst others. ECA and PAUT were selected as the most suitable for the defined used cases. While integrating both NDE technologies into a single inspection head may seem like the ideal solution, it could potentially encounter challenges in overcoming space constraints and introducing complications in processing data from two different NDE technologies. Hence, it is necessary to explore alternative approaches that can enhance the performance of either ECA or PAUT, aiming to streamline the selection process and ultimately narrow it down to a single technology.

The following suggestion are requirement for improving the performance of the selected technologies i.e. ECA and PAUT:

- Customized Probes

Both the results from the survey and the review of literature reveals the probe size and shape would have an impact on the detectability of both selected technologies. Hence, the best fit for purpose probe size and shape needs to be identified and used in each case.

- Multiple frequencies

The use of a single frequency for scanning would limit the selected technology’s ability to detect a wider range of defect sizes. To overcome this challenge an approach that ensures at least two frequencies (low and high frequency) as considered should be adopted in each case.

Based on these results further experimental trials of the down selected NDE technologies will be carried out using manufactured samples with known defects. A standard NDE technology such as radiography would be used to characterize the defects followed by comparison of the selected NDE technologies in this paper.

CRediT authorship contribution statement

Kwame Akowua: Investigation, Data curation, Writing – original draft, Writing – review & editing. **Lee Aucott:** Validation. **David Waillis:** Project administration. **Hery Raphael:** Funding acquisition. **Carrat Remi:** Supervision. **Brau Emmanuel:** Supervision. **Chris Lamb:** Methodology. **Heather Lewtas:** Conceptualization. **Helena Livesey:** Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Scoring criteria

See Tables A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8

Table A.1
Scoring criteria – detectability.

Criteria	Score
Technology has been reviewed before in previous ITER reports. Studies on improving the technology for inspection on ITER has been conducted. Results shows the technologies capability for detecting both backside and near-surface defects in mock-ups.	4
Technology has been reviewed before in previous ITER reports. Studies to improve the technology has been conducted. Results shows the technology could detect most defect in mock-ups used.	3
Technology has been reviewed before in previous ITER reports and could detect some defects in mock-ups used but requires further R&D.	2
Technology has been reviewed before in previous ITER report and results confirm it could detect some defects in mock-ups, however, requires intensive R&D	1
Technology showed no detection potential for all previous mock-up inspections	0

Table A.2
Scoring criteria – environmental tolerances & applicability.

Category	Criteria	Weighted score	Score
Environmental tolerances	No post-inspection cleaning process is required	13%	5
	The performance of technology will not be affected by temperature i.e., survive in temperatures 20 - 80 deg C	6%	
	Radiation hard technology	20%	
	Portable size for in-bore inspection, that is, pipes with diameters ~ 40 mm	29%	
	Inspection can be conducted only from one side	32%	
Applicability	Technology can detect backside and near surface defects in pipes	14%	5
	Technology can detect defect in stainless steel and stainless-steel forging samples	30%	
	Technology has been used in remote handling applications	24%	
	The impact of surface roughness and flatness of samples can be controlled and will not affect inspection outcome.	8%	
	Technology can be used for in-bore, ex-bore and small thickness pipe inspection	24%	

Table A.3
Scoring criteria - material.

Criteria - Material	Score
Technology has been used for inspection defects in stainless steel and stainless-steel forging samples and was successful.	4
Attempt has been made to inspect defects in stainless steel and stainless-steel forging samples using the technology. Some samples were successful others were not. However, the technology requires known improvement activities to ensure high success rate for inspection defects in stainless steel and stainless-steel forging samples.	3
Attempt has been made to inspect defects in stainless steel and stainless-steel forging samples using the technology. Whiles some were successful, further R&D activities needs to be carried out to increase performance.	2
No experience in using this technology to inspect defects in stainless steel and stainless-steel forging samples. However, additional R&D could be carried out as it has the potential.	1
Attempt has been made to inspect defects in stainless steel and stainless-steel forging samples using the technology. Technology was not successful due to factors such as material properties and principle of operation of technology.	0

Table A.4
Scoring criteria - geometry.

Criteria - Geometry	Score
This technology would be successful when deployed to inspect defects in all used cases and their geometries will not affect the performances of the technology in any way	4
This technology would be successful when deployed to inspect defects in some of the used cases. However, others will not be successful due to the geometry. Known improvement activities could be implemented to increase success rate.	3
This technology might struggle inspecting defects in all the use cases due to their geometries. However, R&D could be carried out to increase its performance.	2
This technology might struggle inspecting all the used cases due to geometries. Moreover, no known improvement activities or R|&D could be carried out to increase its performance.	1
This technology may not be successful for inspecting all the used cases due to geometrical features.	0

Table A.5
Scoring criteria - environmental constraints.

Criteria - Environmental constraints	Score
The current state of the technology i.e. its setup will survive when exposed to the environmental constraints mentioned in such section 2.2 such as in high temperature and radiation environment.	4
Improvement such as the used of shielding may be considered when the technology is used in the constraints outlined in section 2.2. However, the performance of this technology will not be directly affected during operation.	3
The performance of this technology would be affected when exposed to the environmental constraints mentioned in section 2.2. However, these constraints might not affect the setup. More R&D activities needs to be carried out.	2
Currently Unknown i.e. more R&D works needs to be carried out to assess the technologies performance in high temperature and radiation environment	1
Both the setup and performances of this technology would be affected when exposed to high temperature and radiation.	0

Table A.6
Scoring criteria – detectability of allowable defects.

Criteria – Detectability of allowable defects	Score
The technology can detect the allowable defect size as well as smaller defects size.	4
This technology can detect the allowable defect size	3
The technology has immense potential to detect the allowable defect size but requires known improvement activities.	2
Currently Unknown i.e. more R&D works needs to be carried out to assess the technology can detect such defect sizes	1
Based on prior experiences, this technology may not be able to assess the specified allowable defect size	0

Table A.7
Scoring criteria – RH compatibility.

Criteria – RH Compatibility	Score
This technology has been deployed using a RHS in previous project	4
This technology has been deployed using a RHS but will require known improvement activities	3
This technology has considerable potential to be deployed using an RHS. Further R&D activities needs to be carried out	2
Currently Unknown i.e. more R&D works needs to be carried out to assess if the technology can be deployed using an RHS	1
Based on previous experiences, this technology is not RHS compatible	0

Table A.8
Scoring criteria – sensitivity.

Criteria – Sensitivity	Score
The quality of results from this technology is not subjected to the presence of weld beads.	4
Weld beads might affect the quality of results when using this technology however, results can easily be improved by known activities	3
Weld beads will affect the quality of results obtained from this technology. R&D activities needs to be carried out	2
Currently Unknown i.e. more R&D works needs to be carried out to understand the impact of weld beads on this technology	1
Technology would not be successful if there are weld beads	0

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