

Reactor performance, system reliability: instrumentation and control

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Abstract. The safe operation of nuclear power plants relies on Non-destructive Evaluation (NDE) of safety critical components in both the initial manufacturing phase and over the reactor’s lifecycle. The conventional approach consists of in-service inspections scheduled at regular intervals, with a periodicity adapted to expected or observed failure mechanisms and their kinetics. The three projects discussed in this paper address and challenge this approach in different ways. iWeld focuses on the inspection of welds and aims to take information about the microstructure of the material under inspection into account to improve the performance of ultrasound inspections. El-Peacetolero designed a hand-held, low power embedded optoelectronic system for an in-situ real-time assessment of aging polymers. FIND aims to develop in-situ instrumentation adapted to the specific requirements of the nuclear power industry and introduces continuous monitoring of metallic pipes to prevent their failure and optimise maintenance. The three projects discussed are at different stages: El-Peacetolero ends in February 2025, FIND just kicked off, and iWeld is halfway in between. In this review, we try to give a high-level introduction, and discuss particular challenges and achievements.

1 Introduction

European-wide nuclear generation facilities are constantly monitored and maintained to ensure performance and safety. Most of the nuclear power plants (NPPs) operation in Europe are in the second part of their operational life and their lifetime can potentially be extended to tens of years if safety and operability of facilities can be guaranteed. Not only must the Generation II power plants need to comply with the increased safety requirements, but also Gen III and future nuclear systems will need to follow these strict regulations also. To achieve safety and long-term operation (LTO) of NPPs, all equipment must keep satisfactory characteristics regarding those specified in the plant design time, with respect to normal operation but also during design basis accidents (DBA) and design extension conditions (DEC) respectively. This requires efforts in terms of ageing management and innovative In-Service Inspection methods. Indeed, most inspection techniques are invasive, time consuming, expensive and restricted to human accessible areas due to geometrical, safety and security limitations.

Innovative Non-Destructive Examination approaches have been proposed and developed in previous European projects, leading to a significant advance in the field. However, for many components of NPPs, NDE has often been designed as an afterthought, rather than being an integral part of the design. This lesson has been learnt, and leads to three interesting paradigm changes:

- continuous monitoring of the structural health of components has demonstrated its added value in other industries (such as aviation/aerospace) as a complement [1] to in-service inspections at programmed intervals and is progressively making its way into the nuclear industry.
- Ageing models, fed with data from continuous monitoring and in service inspections, allow for predictive maintenance (as opposed to scheduled maintenance), allowing a more accurate management of the component lifetime. The question of how to aggregate and use such data has led to the development of digital replica of components.
- Inspection-oriented design, already well-established in instrumentation and control, must be considered at manufacture and for replacement components.

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A more accurate prediction of material damaging and innovative In-Service Inspection (ISI) methods must be leveraged for a safe and economical management of replaceable components. The three European projects i-Welds, EL-PEACETOLERO and FIND address these challenges for different types of materials of prominent importance for LTO.

1.1 iWeld

iWeld (intelligent Welding) builds upon the results of the Horizon 2020 project ADVISE (2017–2022) on ultrasound inspection of complex structured materials, specifically on a proof of concept obtained for structure informed weld inspection. Conventional ultrasound imaging is based on the assumption of homogeneous and isotropic sound velocity within the component to be inspected. This assumption is obviously wrong for welds but simplifies the problem at hand to an extent that real-time imaging is possible. Since the ultrasound beam is affected by the weld structure, which consists of regions with different local sound velocity, using this simplified assumption leads to errors in defect positioning, and to a reduced signal to noise ratio.

Structure informed imaging, on the other hand, takes available information about the structure of a component under inspection into account during the imaging process, in a best effort to compensate for the beam deviations and defocusing induced by the local sound field variations. The quality of the resulting image – in terms of accurate defect localization and sizing, and also signal to noise ratio – will depend on the accuracy of the available information about the microstructure. iWeld addresses thus two technical challenges: how to take information about the actual structure into account in the imaging process in a robust way able to deal with uncertainty, and actually obtaining this information.

Another objective of iWeld is to disseminate this approach to application domains outside the nuclear field. Technology pick-up by inspection service providers is necessary and depends on widespread adoption. To that end, the project receives guidance by an advisory board with members from the oil & gas and the chemical industry. The demonstrator welds have been chosen to be representative of these industries as well (see Fig. 1).

The project was selected for funding by the Euratom Research and Training Programme in 2021 under grant number 101061359 and has a total budget of €1.4 million, with an additional €500 thousand provided by ESPRC for the UK partners. Partners are CEA, Extensior, Transvalor (France), University of Stuttgart (Germany), KTU (Lithuania), the University of Southampton and Imperial College (United Kingdom). The project is coordinated by EDF (France).

1.2 EL-Peacetolero

EL-Peacetolero (Embedded Electronic solutions for Polymer Innovative Scanning Methods using Light Emitting

devices for diagnostic Routines) is funded by the European Commission Directorate-General for Research and Innovation in the topic “NFRP-2019-2020-04: innovation for generation II and III reactors” of the Euratom Program 2019 call identifier “NFRP-2019-2020”. The project has started in September 2020 and will end in February 2025. Its objective is to design and manufacture a TRL7 compact, low power consumption embedded optoelectronic system capable of integrating AI algorithms for in-situ polymer identification and diagnosis of the ageing state of these materials. The system is designed to be used by a non-specialized operator or by a robot. EL-Peacetolero consortium is formed with eight European partners: Forschungszentrum Juelich GmbH (FZJ) The Institute of Energy and Climate Research-Nuclear Waste Management and Reactor Safety (IEK-6), Germany; Universitat Jaume I (UJI), Spain; Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V (FhG-IZFP), Germany; MIRSENSE (MIRS), France; ARTTIC, France; Électricité de France (EDF), France; CEA LIST, France; Sorbonne Université (SU) – Laboratoire Genie Electrique et Electronique de Paris (GeePs), France. The last partner (GeePs-SU) is the project coordinator.

EL-Peacetolero work plan (Fig. 2) is divided into several closely interlinked work packages (WP). The WP1, led by EDF, performs accelerated ageing and Infrared (IR) characterisation, with the Attenuated Total Reflection Fourier Transform IR spectroscopy (ATR-FTIR) of two “industrial use cases” polymers: Neoprene and High-Density Polyethylene (HDPE), which are used in pipe applications. Neoprene is an excellent anti-corrosion coating for steel pipes transporting sea water in the cooling systems in NPPs. Neoprene coating is located at the inner wall of steel pipes and is directly in contact with sea water. HDPE pipelines will be used for transporting water in the cooling systems in NPP. The transported water can come from rivers, lakes or underground water. The ATR-FTIR characterization database is used in WP2 as input for data augmentation techniques and numerical simulations designed to generate a large, simulated, database of ATR-FTIR necessary for training Artificial intelligence (AI) based algorithms for polymer identification, polymer diagnosis, and early detection of the aging condition of polymers. The ATR-FTIR database and the set of aged samples are used as input for WP3, led by GeePs-SU, to define system specifications, design, manufacture and validate the embedded optoelectronic system in WP3. Laser based measurement head and LED based one are developed in WP4 (led by MIRSense) and WP5 respectively. Validation tests on prototypes of the embedded optoelectronic system and assessment of their irradiation hardness are carried out in WP6. WP6, led by UJI, deals with robotic platform design and development.

1.3 FIND

FIND (Future Instrumentation and coNtrol based on innovative methods and Disruptive technologies for higher safety level) aims at developing several instrumentations to support the prevention and the management of nuclear

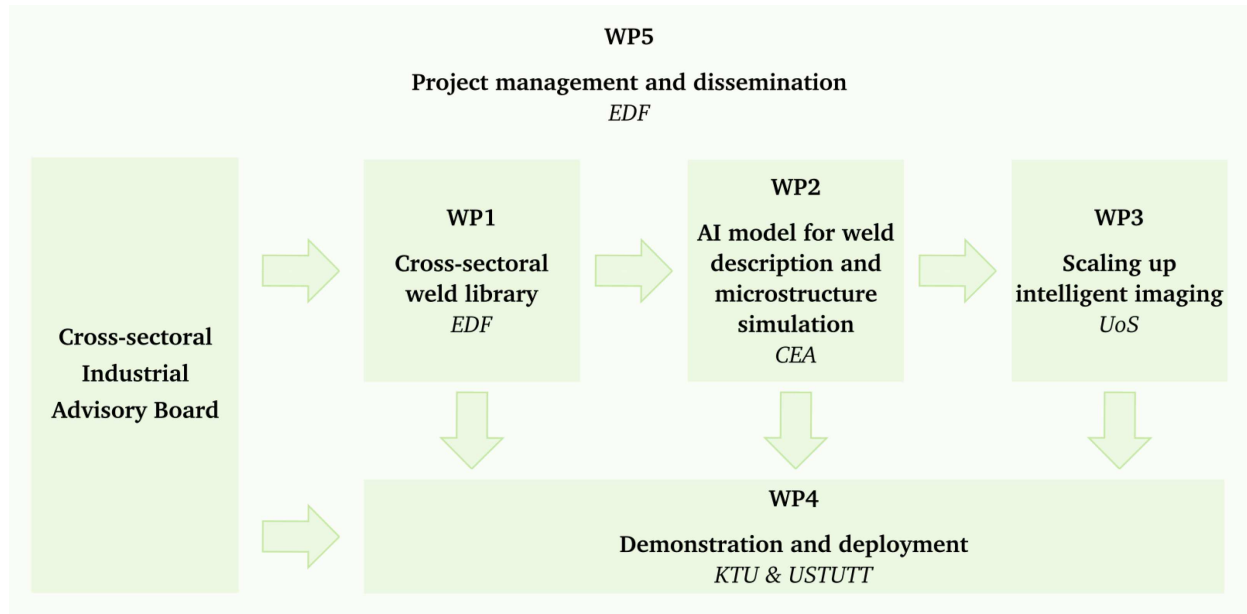


Fig. 1. iWeld project structure.

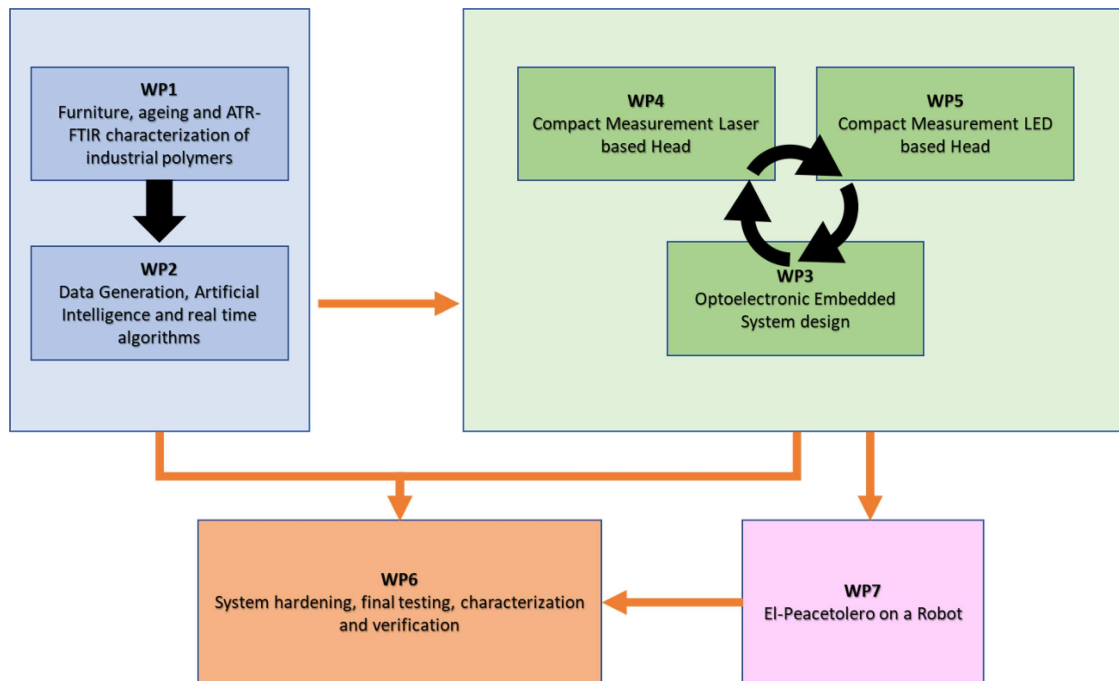


Fig. 2. El-Peacetolero work plan.

incidents and accidents. It has been labelled by the Sustainable Nuclear Energy Technology Platform (SNETP) in 2023 and selected for funding by the Euratom Research and Training Programme in 2024 in the topic “Safety of operating nuclear power plants and research reactors”. It has a total budget of €5.8 million, of which €5 million are provided by the European Commission. It has started in October 2024 for a duration of 4 years. It gathers 11 partners from 7 countries: ASNR (coordinator, France), Framatome GmbH (Germany), the State Scientific and

Technical Centre for Nuclear and Radiation Safety (SSTC-NRS, Ukraine), the Technical Research Centre of Finland (VTT), IPP Center LLC (Ukraine), Commissariat à l’Energie Atomique et aux énergies alternatives (CEA, France), Electricité de France (EDF), the Kaunas University of Technology (KTU, Lithuania), Vuez (Slovakia), Tractebel Engineering (Belgium) and LGI Sustainable innovation (Project Management Officer, France).

FIND addresses three technologies: Structural health monitoring (SHM), Digital Twins and accidental

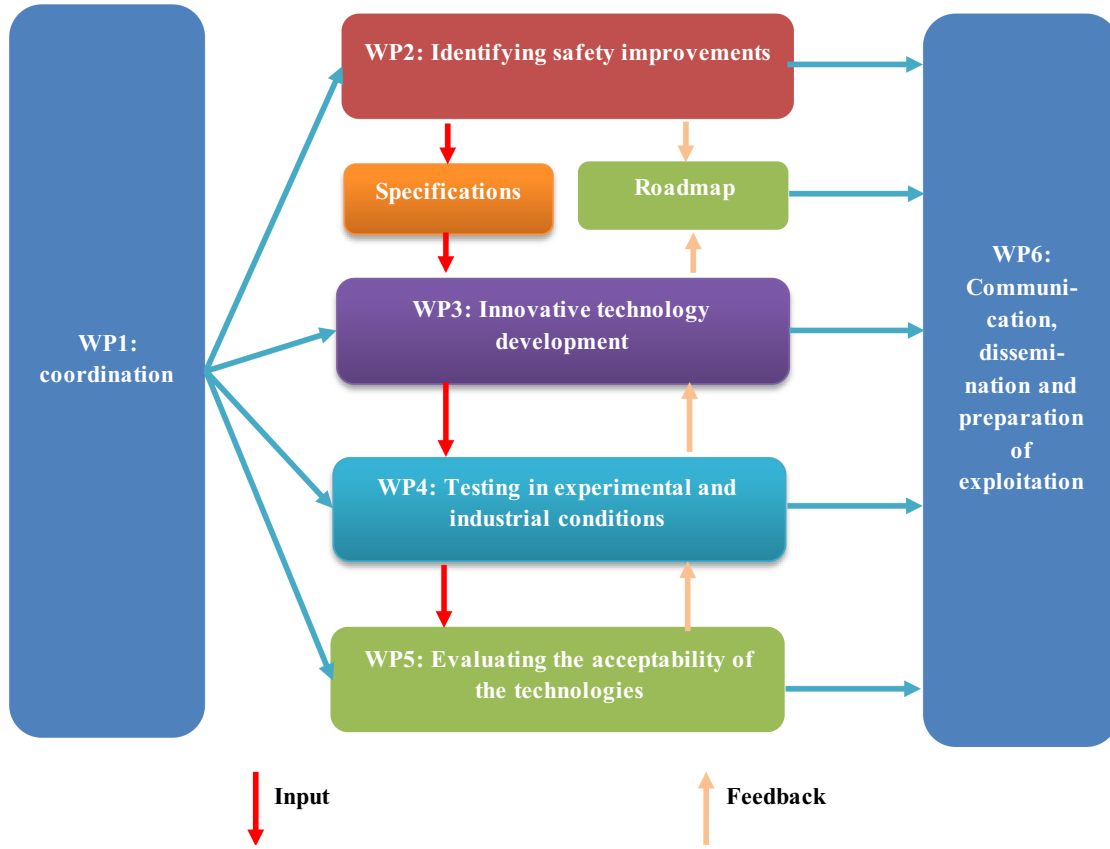


Fig. 3. Interfaces between the work-packages of FIND.

instrumentation. This paper focuses mostly on the two first ones. It is divided into 6 work packages (WP), whose interactions are illustrated by [Figure 3](#):

- coordination (WP1, led by ASNR).
- Specifying the requirements for monitoring technologies to improve safety (WP2, led by VTT).
- Innovative technologies development (WP3, led by CEA).
- Testing in experimental and industrial conditions (WP4, led by Vuez).
- Evaluating the acceptability of technologies (WP5, led by Tractebel).
- Communication, dissemination and exploitation (WP6, led by LGI).

The strength of FIND is to pool up resources for each WP to increase the productivity of the consortium. The elements of the acquisition chains developed in WP3 (probes, embedded electronic systems, data analysis methods...) will be combined differently to address various use-cases defined in WP2. Experimental and industrial tests carried out in WP4 have been optimised to assess several technologies at the same time. Experimental means will be created or adapted to account for possible sources of signal interference (e.g., noise, vibrations) and sensor degradation mechanisms (e.g., irradiation, humidity, heat) faced by continuous monitoring systems due to the plant operation. WP5 will identify the common challenges faced by

the different technologies to be deployed in the nuclear sector, as it has been done in other high-risk sectors [1].

The innovations selected in FIND offer a reasonable perspective for a short-term deployment, while addressing important safety issues and being relatively generic. It is hoped that FIND will open the way for new applications that have not been identified during the project construction or that were considered too challenging. To identify possible follow-up actions for FIND, project partners will be supported by the End-User Group, which is composed of nuclear power plant and fuel cycle facility operators, as well as instrumentation developers, including robotised non-destructive examinations (NDE).

1.4 Crosscutting scientific and organisational challenges

The challenges faced by the three projects are quite different. For El Peacetolero, the challenge is mostly technological; there are no regulatory hurdles to overcome, and it can be safely assumed that the technology will be adopted quickly once the demonstration of its performance has been made. Since no off the shelf solution addresses the issue at hand, prospects are promising.

iWeld confronts a technological challenge: preliminary studies show that structure informed imaging is most valuable for welds with a strong orientation bias, but may

be less relevant for random structures without a favourite disorientation, where arbitrary local beam deviations may average out. This is important to identify use cases where structure information matters. This is a strong argument in favour of applying the technology to dissimilar metal welds, and as an extension, to cast austenitic steel, where stratifications induce a strong bias. This is however beyond the scope of the current project.

FIND is probably the most radical departure from conventional NDE and faces organisational challenges. Introducing structural health monitoring (SHM) represents a break with conventional NDE. SHM consists in acquiring data about the state of a structure or system continuously or on demand, holding the promise to detect defects at an early stage and monitor their evolution, gaining information about defect evolution kinetics at the same time.

Introducing SHM in the nuclear industry also comes with specific challenges. Permanently installed sensors may have to stand a severe environment: heat (up to 320°C for existing light-water reactors), corrosion (for example, sea water for the heat sink or concentrated acid for fuel reprocessing facilities), vibration and potentially high levels of ionizing radiation, including neutrons. Some expected benefits of SHM, like the lower operator dosimetry and the reduced duration of planned shutdowns, can only materialise if SHM replaces some NDEs. This would require a high level of confidence in the results provided by SHM, considering how strictly ISI is regulated. Even if the community has shared best practices [2], this can represent a significant hurdle for their adoption in the nuclear sector. Similarly, a too frequent replacement of SHM systems due to environmental stress would annihilate the above-mentioned advantages and threaten the cost-competitiveness of the systems.

1.5 Industrial impact and end user implication

The three projects use similar approaches to reach out to end users, although the timescales vary.

iWeld has built an industrial advisory board (IAB), which is led by TWI (The Welding Institute), in order to assure dissemination beyond the nuclear field. Another objective of iWeld is to disseminate this approach to application domains outside the nuclear field. Technology pick-up by inspection service providers are necessary and depends on widespread adoption. To that end, the project receives guidance by an advisory board with members from the oil & gas and the chemical industry. The demonstrator welds have been chosen to be representative of these industries as well. In the predecessor project, iWeld had an acquisition system manufacturer as a partner within the consortium, which greatly facilitated implementation. This is not the case in iWeld, and the project has only recently partnered with another acquisition system manufacturer, who will provide an implementation for a demonstrator towards the end of the project. iWeld will either follow the successful approach used in ADVISE organizing a web event (which in 2022 allowed to gather more than 150 attendees all over the world), or organize

a half day event within the annual MPA Seminar held at the University of Stuttgart.

One of the developments El-Peacetolero is expected to produce is a pre-industrial prototype (TRL7) that could be used at EDF's power plants to check the degradation of polymer materials. The initial market of El Peacetolero commercial product will be EDF NPPs and power plants belonging to other companies. El-Peacetolero will also be very useful for automotive and aeronautic industries. The embedded optoelectronic system and the individual components of the tool – such as the LED drivers front-end circuits, ADC block, digital blocks, embedded AI algorithms, LEDs and Laser heads – will be of use for further research and exploitation opportunities and will have an impact beyond the nuclear industry. El-Peacetolero embedded optoelectronic system enables the development of Biosensors and Lab-On-a-Chip for medical applications, such as non-harmful diagnosis of blood for diabetes assessment and non-invasive diagnosis of biological reaction and virus detection. Indeed, detection of the interaction of IR radiation with the biomaterial using spectroscopic techniques such as Simultaneous amplification of surface plasmon resonance (SPR), Localized-SPR, surface enhanced infrared absorption (SEIRA), and many other techniques provide spectral information allowing microbial or virus identification and evaluation of their concentration.

FIND has gathered a large end user group, in line with its objective to screen various technologies and use cases. It is hoped that industrial members of the end-user group will bring successful technologies to the market, or participate in follow-up research projects dedicated to a specific technology of FIND. Ideas emerging during the early phases of FIND but out of its scope may be submitted to the European project CONNECT-NM in Research Line 4 (non-destructive examination and materials health monitoring). The main vector of dissemination will be the final event of the project, to summarise the results of its different steps, including the tests on thermal-hydraulic loops and in industrial conditions. Intermediate results will be disseminated throughout the project in scientific journals and conferences in the fields of nuclear engineering and NDE.

All projects set up public web sites with detailed descriptions of the projects and their publications [3–5].

2 Structure-informed ultrasound imaging

Ultrasound NDE is in the process of replacing traditional phased array ultrasound imaging with TFM (total focusing method) imaging. Phased array imaging uses physical beamforming, applying adapted delay laws to each transducer element, to obtain focusing and beam deviation at a given depth and angle. Imaging in then consists of simply concatenating A-Scans, or at best to project A-Scans along the refracted angle, which is particularly attractive for sector scans. The sound velocity is always assumed to be constant and isotropic in these images.

With TFM imaging, synthetic beamforming is applied on the full matrix capture raw data, which basically consists of the data received by each individual transducer

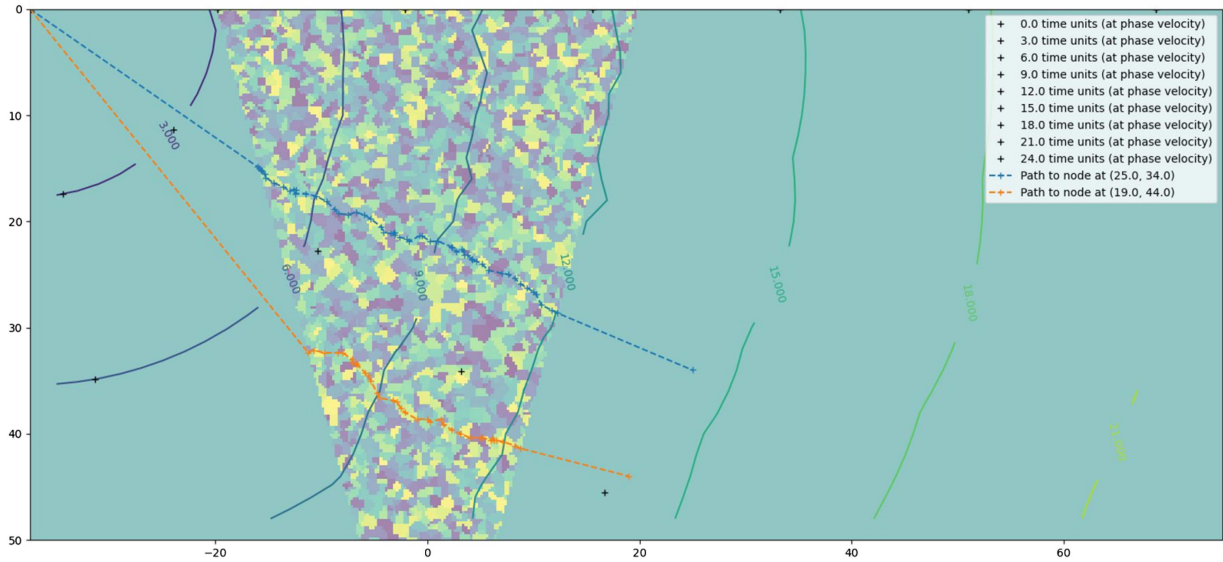


Fig. 4. FERMAT Paths across a moderately heterogeneous weld.

element, for each transducer element when it acted as a transmitter. Focusing on each location within the reconstruction zone is obtained by using “delay and sum” – each signal is delayed the exact time necessary to ensure that all signals arrive at the same time. This requires calculation of the travel time between the transmitter, the observation point, and the receiver for each couple of transmitter and receiver, and for each observation point. Modern acquisition systems carry out this operation in real-time: they can do this because they assume a constant and isotropic sound velocity within the component to be inspected. This assumption breaks down in anisotropic welds, where the sound velocity depends on the local grain orientation. As a result, incorrect delays are applied, reducing signal to noise ratio and leading to positioning errors for reflectors such as defects.

Structure informed ultrasound imaging addresses these issues by taking the actual local wave velocity into account in the imaging process. Mathematically, this requires determining the path of shortest travel time between two points in a heterogeneous medium, which is also referred to as a FERMAT path, or a path satisfying FERMAT’s law of stationary travel time. Building upon results obtained in the predecessor project ADVISE, iWeld has developed methods to determine these FERMAT paths, using either forward ray tracing (for smoothly heterogeneous material descriptions) or an Eikonal solver. Figure 4 gives an example of two FERMAT paths for two different positions and a configuration where the ultrasound signal must travel through a weld.

But this is only one of the building blocks required to actually do structure informed imaging. We also need to obtain the information about the weld structure. The traditional way to obtain information about the microstructure consists in manufacturing a representative mock-up, ideally using the exact same manufacturing process, and to destructively characterize its microstructure, using methods such as EBSD (electron backscatter diffrac-

tion) or metallography. It is common to use easier to manufacture plane mock-ups instead of reproducing the exact geometry. Since a single mock-up will not allow to capture the statistical variability of influential parameters, the qualification process often uses computer modelling to study the impact of influential parameter variation around the nominal value reflected by the mock-up. Obvious influential parameters are variations of the weld chamfer geometry, the tolerances of which are usually known. For manual welding, the list of influential parameters is considerably larger, including variations of the welding speed, the torch angle, etc.

iWeld pursues two additional approaches to obtain the microstructure. The first research avenue uses weld simulation and uses the welding procedure with information about process parameters such as the weld chamfer, torch energy and displacement speed, filler material, passes etc. to simulate the melt pool and the subsequent solidification process. Among other results, such as residual stress levels, this allows to obtain a virtual microstructure, capturing local grain size and grain orientation, which can serve as input to the structure informed imaging algorithm. A number of realizations will be necessary to take the variability of influential parameters into account, but this is cheaper and faster than producing the same number of mock-ups. Figure 5 shows an example showing the smaller grains in the base metal and the larger, elongated and oriented grains within the weld, which will deviate the ultrasound beam. This example has been obtained using Transvalor’s Transweld software coupling thermal and microstructure simulation using a welding procedure for a typical V-weld using 316L alloy steel.

A second approach to obtain the microstructure is coined weld tomography; an appealing, but somewhat misleading name: It consists in iteratively matching ultrasonic time of flight data calculated by ray tracing through a parametric weld model with actual time of flight measurements. As the problem at hand is inherently ill-posed,

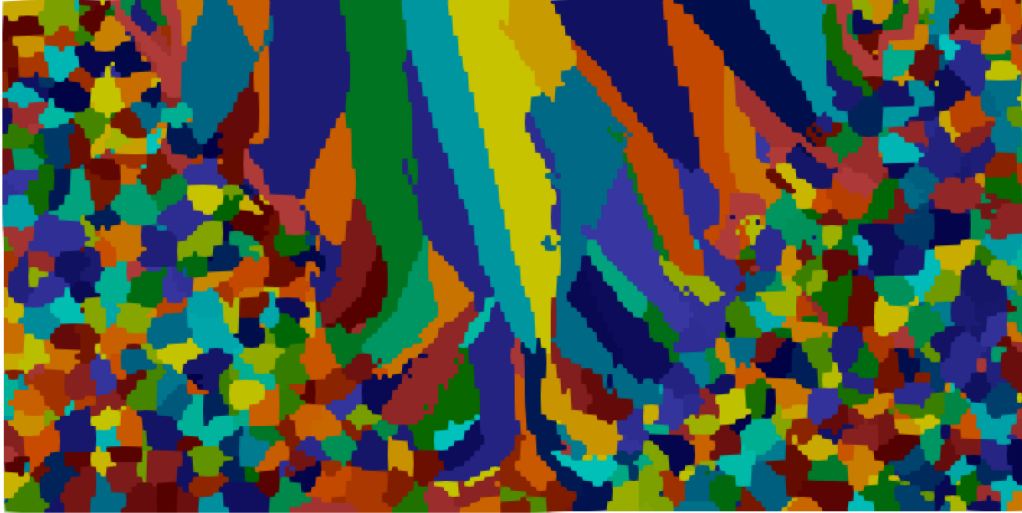


Fig. 5. A simulated weld.

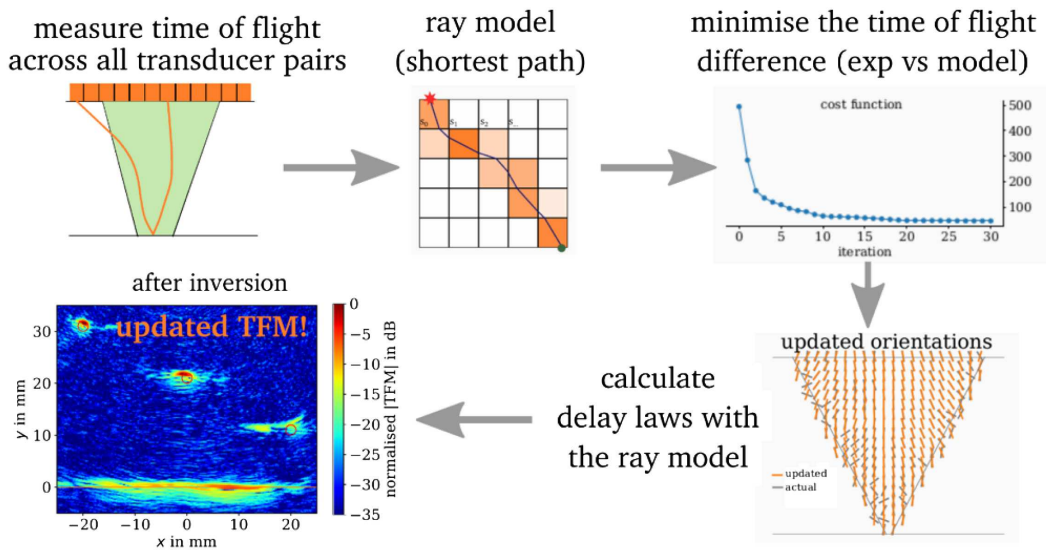


Fig. 6. Weld tomography.

this is difficult and works best if the initial guess is not too far from reality, and if the number of parameters of the weld model is low. Figure 6 illustrates the approach: ultrasound time of flight data is obtained between transmitting and receiving elements of a phased array transducer. At the same time, shortest path ray tracing is used to obtain theoretical time of flight information on a discretized weld representation in a computer. The difference between this theoretical time of flight information and the measured data for all transmitter-receiver pairs is used to construct a cost function, the minimum of which we must find. The discretized weld description is iteratively updated, until a minimum for the cost function is found. Once this is done, the resulting microstructure description is used in the structure informed TFM imaging algorithm.

The enhancement of the resulting image will depend on the impact of the microstructure has on the ultrasound

beam. Figure 7 shows a comparison of conventional TFM and structure informed TFM on a 51 mm thick austenitic weld from EDF, into which three side drilled holes have been bored as artificial reflectors. We observe that the structure informed image has less noise, and the locations of the side drilled holes are predicted more precisely. The improvements are less pronounced for thinner welds than for thicker welds, and also less pronounced for perfectly symmetric welds (V or X-chamfer) than for asymmetric welds (K-chamfers, J-welds).

With both approaches having their challenges, it is obvious that structure informed imaging must be able to deal with uncertainty and errors, as it is impossible to obtain a perfect description of the macrostructure. A combination of both approaches – using a weld simulation to obtain a nominal microstructure, converting it into a parametric description, and then adjusting the model using weld tomography – might be an answer to this

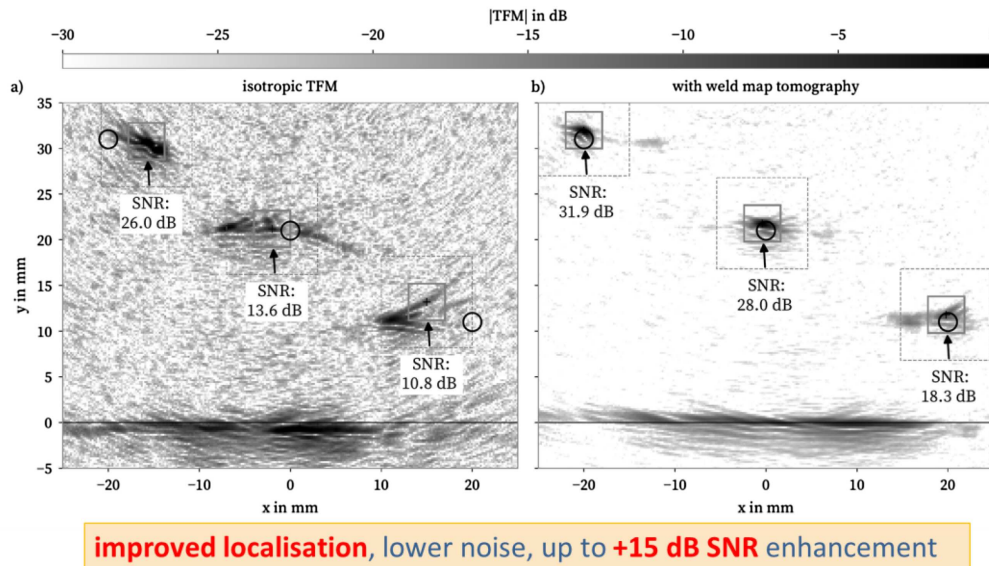


Fig. 7. Standard TFM image (left) and structure informed TFM (right).

challenge. Current work focuses on machine learning techniques to produce an intelligent interpolation of weld realizations in a parametric space with lowest dimensionality possible.

The demonstrator weld used in the project – and currently under manufacturing – has been voluntarily chosen to represent industry sectors other than nuclear as well, including oil and gas and the chemical industry.

3 Polymers monitoring for NPPs safety and Long-Term Operation (LTO)

3.1 Context

Polymer ageing is one of the crucial aspects to be verified for the safety and long-term operation (LTO) of Nuclear Power Plants (NPPs). These materials are widely used as protective, sealing or isolating coatings in a lot of equipment such as electrical cables or pipes throughout the nuclear facilities. For example, it is essential that the cables operate in case of an accident to keep control of the reactor [6]. Up to now, existing control methods meets the criteria of reliability, but they are invasive, expensive, and time-consuming. Furthermore, they are restricted to human accessible areas due to geometrical, safety and security limitations. Early detection of abnormal behaviour and embrittlement are therefore impossible with these approaches that cannot afford on-site investigation and real-time monitoring and analysis of polymers. It is therefore evident that there is a pressing need for the development of a system capable of performing non-destructive identification and diagnosis of the ageing state of polymers on-site. This system would serve to support modernisation, optimisation and the efficient implementation of safety requirements within the European nuclear industry.

3.2 Concept and methodology

El-Peacetolero project proposes an alternative solution for polymer ageing diagnosis to overcome the limitations mentioned above. Its principal objective is to design an embedded optoelectronic system that performs non-invasive monitoring and analysis of polymers used in industrial environments. El-Peacetolero principle of operation [7] consists of: (a) illumination of the polymer by monochromatic infrared sources (LEDs, Lasers) emitting at specific wavelengths related to ageing behaviour; (b) detection of the reflected IR radiation with one or more IR photo-detector; (c) the signal is then amplified, converted to digital data, and analysed in order to extract polymer absorbance according to Attenuated Total Reflection (ATR) measurement technique; (d) Embedded Artificial Intelligence algorithms are deployed for polymer identification and ageing check and monitoring from absorbance measurements at the specific wavelengths. The final prototype of El-Peacetolero will be a TRL7 hand-held, low power, embedded optoelectronic system that can be used by a technician or installed in a robot to perform non-invasive monitoring and diagnosis of polymers in a constrained and complex environment.

The development of the embedded optoelectronic systems poses several challenges in different scientific fields. El-Peacetolero brings together experts in material science, data science and AI, microelectronics, optoelectronics and robotics to overcome scientific and technological obstacles and achieve the project's objectives.

The methodology defined by the consortium consists of the following steps:

- (a) perform Accelerated ageing on two industrial use cases polymers (Neoprene and HDPE) to form a set of aged polymer samples at different ageing states and carry ATR-FTIR spectroscopy to build a database of IR spectral characteristics of these samples;

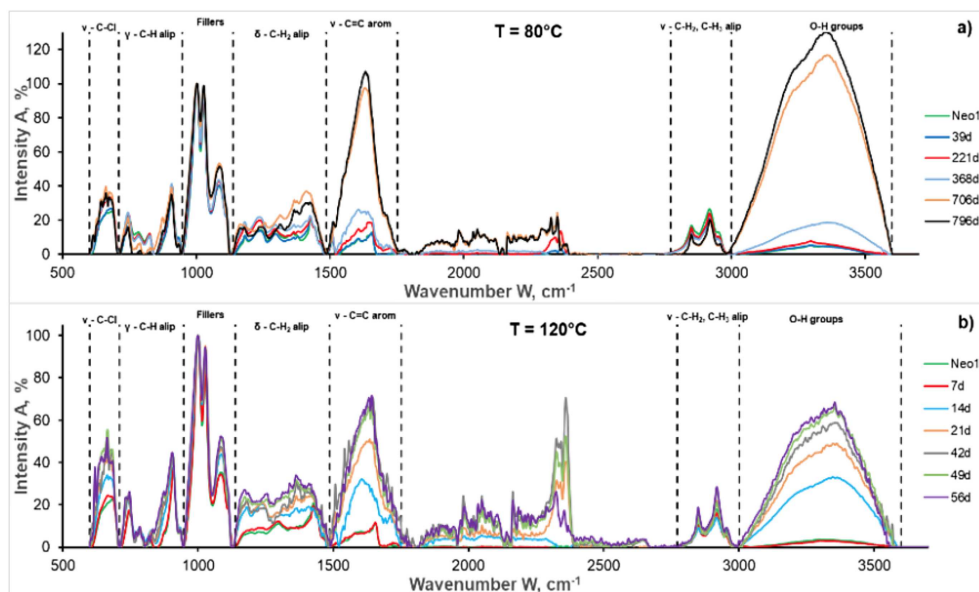


Fig. 8. The evolution of FTIR spectrum during aging at (a) 80°C and at (b) 120°C.

- (b) derive system specifications according to these “industrial material uses cases” IR characteristics: such as specific wavelengths, Signal to Noise Ratio (SNR), Analog to Digital Converter (ADC) resolution, etc. . . These specifications have been strongminded thanks to close collaboration and the know-how of the project team in the complementary fields mentioned above;
- (c) the ATR measurements are then augmented to form a huge ATR data base needed to train AI identification and diagnosis algorithms. Machine learning, and AI will be then used to develop real time identification and diagnosis algorithms.

The following step are the component technology development during which the technological challenges need to be solved. This concerns both hardware and software development and consists of:

- (d) design and development of the El-Peacetolero compact and modular measurement head – The measurement head contains IR optical sources, ATR crystals, IR detectors and a heatsink.
- (e) Design and development of embedded electronic system – This concerns Analogue circuits, Analogue to digital conversion, System control, data transfer and data display, Embedded AI algorithm implementation. Another issue will be system hardness for resistance to radiation.

3.3 El-Peacetolero results and achievements

3.3.1 Accelerated ageing of two use case polymers

3.3.1.1 Set of aged samples & ATR-FTIR spectra database

The two materials of growing interest for pipe applications in nuclear power plants (NPP) identified for our study are

neoprene and HDPE. An accelerated ageing program is proposed by EDF for both thermo-oxidative ageing and immersion ageing at 40 and 80°C. The thermo-oxidative ageing is carried out in two ovens. The immersion ageing is performed in two test loops that EDF built inside its Polymer laboratory. The first test loop is called Guerande Loop in which chlorinated synthetic seawater is used for the immersion ageing of Neoprene and HDPE samples. The second test loop is called Raw Water Loop in which reconstituted river water is used for the immersion ageing of Neoprene and HDPE samples. Additionally, accelerated thermo-oxidative ageing at 120°C is carried out on Neoprene samples at FZJ laboratory. ATR-FTIR measurements are performed directly on the two surfaces of the samples (Neoprene plates and HDPE discs) at EDF polymer laboratory. The same ATR-FTIR characterizations were performed by FZJ team in their laboratory.

A database of FTIR measurements is built and it is used for data augmentation in WP2 and for system specification in WP3-WP4-WP5. The corresponding aged samples are used for prototype evaluation.

3.3.1.2 Toward “El-Peacetolero” ageing detection threshold

Thermo-oxidative and immersion aging of neoprene and HDPE samples proceed by different aging mechanisms, which is reflected in the changes of their IR spectra. As an example, Figure 8 shows the evolution of the IR spectra of neoprene samples during thermo-oxidative aging at 80 and 120°C. The IR spectrum can be divided into seven distinct regions. Two groups of reflexes, namely C=C-aromatic with a characteristic absorption band at 1630 cm⁻¹, which is associated with the formation of double carbon bonds during thermo-oxidative aging, and the O-H group are the most sensitive to the aging processes of neoprene. The intensity of other reflex groups also increases, but insignificantly. The results of IR spectra analysis show

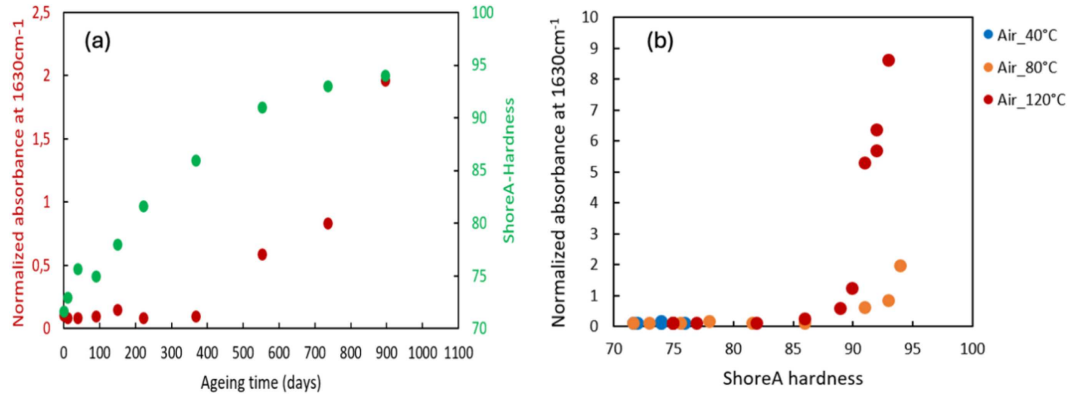


Fig. 9. (a) Normalized absorbance (by 1001 cm^{-1}) at 1630 cm^{-1} and Shore A hardness as a function of ageing time at 80°C . (b) Normalized absorbance at 1630 cm^{-1} as a function of the Shore A hardness of neoprene samples under thermo-oxidative ageing.

that thermo-oxidative aging proceeds faster with increasing temperature as observed in Figure 8.

In order to gain insight into the physical and chemical processes occurring in the material during its ageing, polymer samples (Neoprene) were subjected to investigation in the EDF Polymer laboratory, with hardness measurements taken on the Shore A scale. Additionally, in FZJ, destructive diagnostic methods were studied, including the compressibility of the material and the construction of the corresponding $P - \epsilon$ diagram, as well as the determination of Young's modulus (E) values. In these studies, particular attention was paid to the development of critical ageing criteria for the material, with a specific focus on its dependence on temperature and ageing time.

This study aimed to investigate the correlation between the spectral characteristics (IR) and the strength characteristics (Shore A hardness) of neoprene samples. Figure 9a illustrates dependence of the normalized absorbance (by 1001 cm^{-1} —silanol groups of kaolin fillers inside of neoprene samples) at 1630 cm^{-1} and Shore A hardness as a function of ageing time at 80°C . Figure 9b illustrates the relationship between the normalized (by 1001 cm^{-1}) absorbance at 1630 cm^{-1} and the Shore A hardness of Neoprene samples subjected to thermo-oxidative aging. The results demonstrate that the ageing process occurs in two distinct stages. The initial stage is characterised by a curing time of 0 to 365 days at 80°C . The absorption intensity at 1630 cm^{-1} shows no modification (absorbance ~ 0) in comparison to the starting material, while the Shore A hardness rises from 72 to 86. It can be assumed that at this stage, organic additives (antioxidants and plasticizers) are removed from the material and polymer oxidation is not significant. The removal of organic additives leads to a decrease in the elasticity of the polymer and, consequently, to an increase in its hardness.

The second stage is characterised by a curing time of over 365 days at 80°C . At this stage, there is a noticeable increase in the absorption intensity at 1630 cm^{-1} , which indicates the course of polymer oxidation processes [8,9].

The aging process of the polymer due to these chemical processes leads to an increase in hardness up to 93.

The first point of this second stage is characterised by an ageing time of 552 days at 80°C which corresponds to the Neoprene oxidation detection threshold for IR spectroscopy in the framework of El Peacetolero project. The corresponding Shore A hardness is 91, and the normalized absorbance at 1630 cm^{-1} is 0.59. In the experiments conducted at elevated temperatures (120°C), the investigated parameters exhibited similar values (normalized absorbance at 1630 cm^{-1} is 0.56; Shore A hardness is 89) in the samples after 28 days of material aging. Furthermore, tensile testing revealed that the neoprene sample exhibited a loss of approximately 50% of its initial relative elongation at break value (0.12 to 0.055) after 552 days of curing at 80°C .

Additionally, the correlation between mechanical characteristics (Young's modulus E) and infrared spectrometry data (total area for the aromatic reflex group $\text{C}=\text{C}$) was investigated. It was demonstrated that there is a direct correlation between these parameters during the second stage of the ageing process.

In light of these findings, it can be assumed that during thermo-oxidative ageing of Neoprene samples, when the relative elongation at break diminishes significantly from its original value, the Neoprene sample might probably not be able to guarantee its mechanical properties. It can therefore be proposed that a value of 0.5 of the corresponding normalised (by 1001 cm^{-1} —silanol groups of kaolin fillers inside of neoprene samples) absorbance at 1630 cm^{-1} represents the threshold for the Neoprene oxidation detection by IR spectroscopy in the framework of El Peacetolero project, based on the El-Peacetolero measurement results.

3.3.2 Embedded optoelectronic system design

3.3.2.1 System architecture

The architecture proposed, by GeePs-SU, to meet the specifications is presented in Figure 10, it consists of three principal blocks: analog PCB incorporating IR LED drivers and Thermo-electrical Cooling (TEC) control circuits; data acquisition block incorporating the

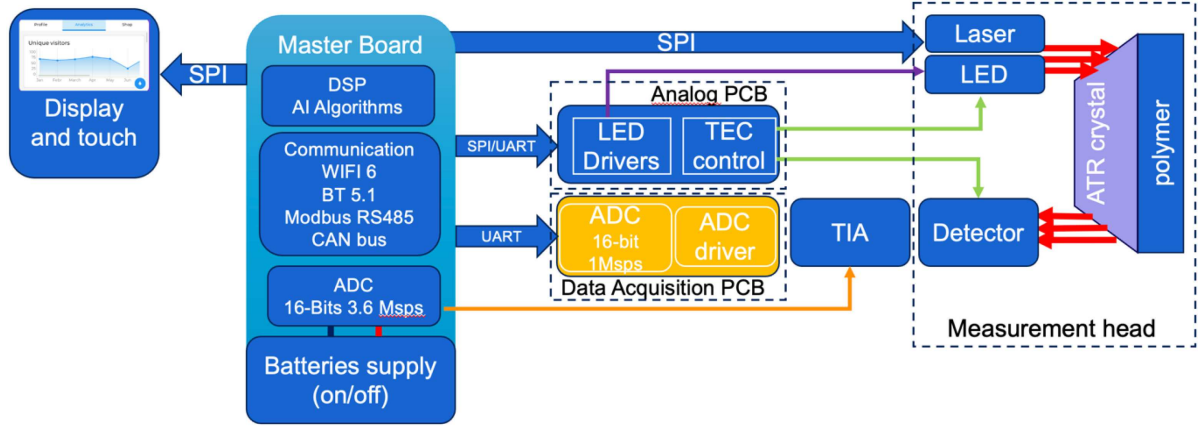


Fig. 10. Synoptic & architecture of El-Peacetolero embedded optoelectronic system.

16-bit ADC and its drivers; and a master bloc ensuring system control, digital signal processing, AI algorithms implementation, communication, data transfer and display.

3.3.2.2 Compact hardware for Edge computing and Tiny ML

GeePs-SU team proposed the development of El-Peacetolero embedded optoelectronic platform on a System In Package module (SIP) to afford compactness, high performance, low power consumption and robustness against radiations. The proposed SIP has two integrated 16Bit 3.6 Msp SAR ADCs. It has two Arm cortex processor, an 800 MHz Arm® Dual Cortex®-A7 and a 200 MHz Arm® Cortex®-M4. It has also an Arm® NEON Co-processor which accelerates and speeds up signal processing and deep learning algorithms. It has also a 3D GPU 533 MHz Vivante® – OpenGL® ES 2.0 to handle and accelerate matrix computing and display. It integrates A TrustZone® processor ensuring operating system security. This provides a hardware platform for Edge computing and Tiny ML. Elpeacetolero hardware platform for Edge computing and Tiny ML has been designed, manufactured and tested successfully, it is presented in [Figure 11](#).

3.3.2.3 Radiation hardness evaluation

We defined a mission scenario for using the prototype in an irradiated environment in order to calculate the cumulative dose to which the prototype could be exposed during an operating life of 20 years. The calculated Total Ionizing Doze (TID) absorbed by the device will reach 20 Gy over this life time. We set the required hardness level of the Embedded optoelectronic system to 100 Gy in order to have a sufficient safety margin. To evaluate El-Peacetolero prototype hardness, irradiation test was performed on El-Peacetolero Integrated Circuits (IC) at the facility of LABRA in CEA INSTN. The test boards of each selected IC were placed in the irradiator during the irradiation tests as depicted in [Figure 12](#). Pre-irradiation, online, and post irradiation tests was collected for all the tested components. Test results show that at least one reference of

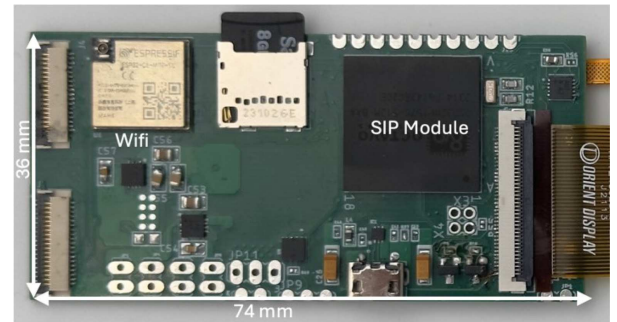


Fig. 11. Photography of El-Peacetolero PCB platform for Edge computing and Tiny ML.

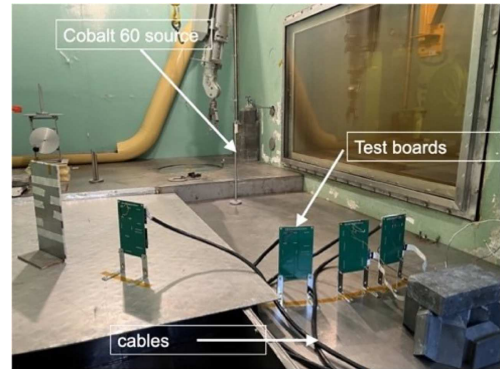


Fig. 12. Test boards placed in the irradiator during radiation tests.

each IC is able to sustain the limit amount of 100 Gy cumulated dose [10], except for one, which would need to be replaced in the final design. However, the results also showed that the limit is reached only because the criteria is particularly restrictive.

3.3.3 Compact Multi-Lambda QCL Laser head

In order to demonstrate the optoelectronic system industrial feasibility a compact, high collection efficiency measurement head including the IR emitting sources LEDs

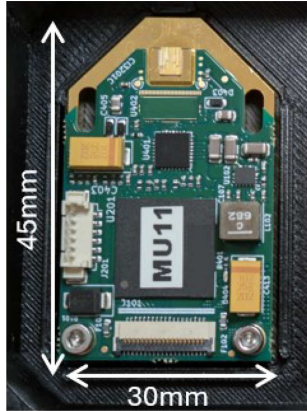


Fig. 13. Photography of the Multi-Lambda QCL source Laser PCB's.



Fig. 14. Prototype 1 in the demonstration to inspect the exterior of a pipe.

and Quantum Cascade Laser (QCL) emitting at the specific wavelengths, ATR crystal and IR detectors needs to be designed and built. Two heads will be designed and tested to compare their performance at TRL7, one using compact/minature, low cost InfraRed (IR) LEDs and IR detectors and a second using IR Quantum Cascade Lasers (QCL). The aim is to fabricate the lasers chips that will be used in the final prototype of the EL-PEACETOLERO project. According to the study performed by EDF&GeePs-SU&FZJ, a list of targeted wavelengths was established: 1730 cm^{-1} ($5,78\text{ }\mu\text{m}$); 1647 cm^{-1} ($6,07\text{ }\mu\text{m}$); 1086 cm^{-1} ($9,21\text{ }\mu\text{m}$); 1002 cm^{-1} ($9,98\text{ }\mu\text{m}$). For each wavelength mirSense has fabricated the QCL lasers.

MIRSense performed the design of the compact lens for 4 wavelengths targeted in the EL-PEACETOLERO project: $1730\text{ cm}^{-1}/1647\text{ cm}^{-1}/1086\text{ cm}^{-1}/1002\text{ cm}^{-1}$. For each wavelength, we achieve different designs of the lenses to determine the limit of our process. The laser integration has been designed as an independent unit called "MLS" (Multi-Lambda Source) integrating this new component as depicted in Figure 13. It consists into an autonomous device handling multiple laser source. The size of this unit is 45mm long and 30mm wide. The volume of the device compared to the electronic at the beginning is divided by a factor 50. The level on integration achieve here is a big step towards the integration of the quantum cascade lasers. Thanks to the QCL Electronics design recommendations achieved in the

project, a first batch of prototypes have been assembled. The challenge of these assemblies was to define the different process use for each building blocks (laser chip on submount, submount on copper plate, ASIC on PCB and PCB on copper plate).

3.3.4 El-Peacetolero on a Robot

A working tele-robotic prototype that permits inspections of pipes with the El Peacetolero tool presenting three main configurations to cover interventions: (1) outside a pipe, (2) inside a pipe without water, and (3) inside a pipe full of water.

The design of the tele-robotic prototype (Fig. 14) is being performed as expected, having finished the simulation server and the human-robot interface. Also, the communications and localization experiments are under construction, providing already some experiments based on omni-wheels odometry, and 4G/Wifi/Bluetooth/LORAWan/umbilical technologies. Next studies will continue on localization and communications, especially focusing on the software network architecture, by using advanced protocols for Telerobotics.

4 FIND: continuous monitoring technologies as a complement to in-service inspection

4.1 Ultrasonic methods to detect defects in metallic pipes

FIND will work on the adaptation of various ultrasonic SHM technologies to the constraints of the nuclear sector, targeting different types of metallic pipes and damage mechanisms, for which current ISI methods face shortcomings. The project knows the introduction of SHM as a complement to traditional ISI represents a paradigm shift.

Two partners will develop technologies to control ferritic raw water pipes, which transport untreated sea or fresh water to cool down different systems of the plant. They operate at low temperature and pressure and without any exposure to radiation. However, they can be affected by rapidly evolving corrosion mechanisms, like crevice corrosion. Large sections of such pipes are usually buried, other parts can be hidden by support structures or wall penetrations, making them difficult to inspect. To address those concerns, FIND will explore two SHM methodologies. KTU will develop a high-order guided-wave inspection system using piezoelectric transducers. This technology can detect small defect over a few meters. Laboratory tests on real samples and on the thermal-hydraulics loop Viktoria [11] (operated by Vuez) will be completed by on-site measurements in French NPPs (EDF). In addition, SSTC-NRS will improve an acoustic monitoring system for leak localisation. Tests will be carried out on representative urban water supply networks.

Guided-wave technologies will also be investigated by CEA to monitor flow-accelerated corrosion on the high-pressure turbine extraction line. To withstand the harsh measurement conditions (temperature, vibration), CEA will use Fibre Bragg Grating (FBG) sensors on optical

fibres. CEA manufactures its own devices thanks to a high energy pulsed laser. Since FBG sensors cannot emit acoustic signal, CEA will use passive tomography exploiting the ambient elastic noise of the installation to reconstruct a 2D thickness map of the pipe [12,13]. Tests are planned on the above-mentioned Viktoria loop, to account for signal interference caused by the inherent noise of the installation (pumps, water movement, etc.). A prototype is planned to be installed in a Belgian NPP, thanks to the support of Tractebel.

The last ultrasonic method addressed in the frame of FIND will be acoustic emission [14], to detect crack growth events on the safety injection line of reactors, thanks to FBG sensors (CEA) and rad-hard piezoelectric sensors (Framatome GmbH). Tests will be conducted on an accelerated corrosion loop operated by VTT.

4.2 Feeding degradation models with real data: towards a digital twin

The design of a safety system requires to confront assumptions about the stresses experienced by the material in operation with degradation models. This approach faces two inherent limitations that can degrade the quality of predictions. First, the stresses faced by the material are rarely measured in real conditions, which makes it impossible to confirm design assumptions. Second, degradation models like ageing models are often based on experimental data, which cannot fully represent the complexity of industrial conditions. Some stresses may not be simulated (like irradiation, especially if coupled with mechanical degradation), scale effects must be extrapolated to real-size components and degradation kinetics must generally be accelerated artificially. These simplifications can affect the transposability of degradation models to industrial set-ups.

In-situ monitoring of the most influential stresses affecting a material can provide information that is at the same time fully representative of industrial conditions with a level of details close to an experimental set-up. Combined with a detailed numerical model, they can form an accurate Digital Twin of the component.

4.2.1 Quasi-static data acquisition

The first implementation of these concepts in FIND concerns the “universal monitoring system” developed by IPP Center LLC. The instrumentation is dedicated to the reconstruction of the strain and stress fields in buried pipes that are affected by soil movements [15]. Strain gauges located at strategic positions collect information about local deformations. It is then used to feed a detailed finite elements model of the pipe, to calculate stress concentration zones that may threaten its integrity. In the frame of FIND, this concept will be adapted to buried raw water pipes. Systems will be tested in representative conditions with oil and gas transport networks in Ukraine.

4.2.2 High-frequency data collection

Thermal and mechanical fatigue can affect several components of NPPs, especially on the primary circuit: pressuriser expansion line or safety injection system for example. The characteristics of the thermal and mechanical cycles experienced by pipes are hard to predict. Therefore, acquiring more data is crucial. In-situ monitoring of fatigue is challenging, because it implies to track high-frequency phenomena. The quantity of raw data generated can rapidly become intractable. Embedded data analysis can overcome this limitation and allow the transmission of aggregated data only.

IPP Center LLC and Framatome GmbH will develop complete acquisition chains and test them on an experimental thermal stratification loop developed by IPP Center LLC in Ukraine and at the Tihange NPP in Belgium. The experimental set-up will be used to benchmark approaches based on the FAMOS-i technology developed by Framatome and on extensometers developed by IPP. Industrial tests at Tihange aim at proving the performance of accelerometers (including the FAMOS-V system developed by Framatome) in challenging industrial conditions. Systems will be installed on the extraction line of the high-pressure turbine of the plant (for demonstration purposes only, since vibrational fatigue is not identified as a key degradation mechanism for this pipe). The data collected will be assimilated by analytical or semi-analytical fluid and solid mechanics calculation codes to reconstruct the stress field in the pipes.

4.3 Accidental instrumentation

FIND also explores synergies with accidental instrumentation, which exploits same technologies and scientific knowledge as SHM: embedded electronics, advanced signal treatment, hardened material, etc. The scientific programme includes the use of heated thermocouples for water level measurement and steam leakage localisation in accidental conditions, developed by Vuez and tested on its Viktoria loop, that will be substantially modified for FIND. ASNR will develop a Metallic-Organic Framework-based sensor to detect fission products in the containment building of the reactor during a severe accident. The manufacturing of the sensor and laboratory tests will be carried out by two mixed research units hosted by the university of Lille (France), in partnership with ASNR.

4.4 Robustness tests

The robustness of sensors will be tested in the IRMA irradiator operated by ASNR, which can deliver radiation doses representative of severe accidents, possibly coupled with heat and steam. The layout of the irradiation chamber allows to irradiate many instrumentations simultaneously with different dose rates, while testing them online.

5 Conclusions and follow-up issues

The lifetime extension of currently operating plants to 60 years and beyond has become a reality in many countries. The long-term operation of these plants has initiated some interesting paradigm changes:

- structural health monitoring, already well established in other industries, will progressively be introduced into the nuclear industry, albeit at a slower pace and only where it is economically viable.
- Long-term operation has also raised questions about non-metallic materials hitherto not considered as of concern, with polymers being a prominent example.
- Manual inspections are progressively replaced by encoded and/or automated inspections to improve traceability and repeatability.
- Increased use of Artificial Intelligence for advanced signal treatment to push detection limits and acquire more meaningful information, provided that the trustworthiness of the methods can be guaranteed and demonstrated.
- Increased knowledge about failure mechanisms and failure kinetics, and the availability of ageing models, has paved the way to predictive maintenance (as opposed to scheduled maintenance with conservative pre-defined inspection frequencies).

Looking further ahead, the incorporation of the above-mentioned innovations in compact autonomous embedded systems may address challenges in constrained environments. Introducing innovation in the nuclear industry comes with strong requirements. A detailed scientific understanding is necessary but not sufficient: the robustness of the end-to-end process must also be proven to regulatory authorities. Successes in other high-risk industries like aeronautics show that such evolutions are possible, though with significant efforts and over an extended period of time. A discussion between operators and regulators will be necessary to determine if some pre-existing controls can be abandoned to increase operating performance. The demonstration that the new practices globally have a positive impact on safety will probably be required.

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Conflicts of interest

The authors declare having no conflict of interest related to the work presented in the article.

Data availability statement

Data associated with this article cannot be disclosed due to legal reason.

Author contribution statement

B. Poubeau, coordinator of FIND. A. Schumm, coordinator of iWeld. M. Ben Chouikha, coordinator of El Peacetolero.

References

1. *Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft*, SAE International, ARP6461, <https://www.sae.org/standards/content/arp6461/>
2. B. Chapuis, P. Calmon, F. Jenson, *Best Practices for the Use of Simulation in POD Curves Estimation* (Springer, 2018)
3. Website of El Peacetolero: <https://www.el-peacetolero.eu/>
4. Website of iWeld: <https://iweld-euratom.org/>
5. Website of FIND: <https://find-project.eu/>
6. M. Broudin, M. Ben Chouikha, Methodologies for efficient and reliable NPP polymer ageing management, EPJ Nuclear Sci. Technol. **8**, 22 (2022)
7. A. Ribes Cortes, M. Ben Chouikha, Portable device and method for estimating a parameter of a polymer, France Patent WO2 018 091 631(A1), TW201 827 809 (A), FR3 059 104 (May 25, 2018)
8. M. Celina, et al., Correlation of chemical and mechanical property changes during oxidative degradation of neoprene, Pol. Deg. Stab. **68**, 171 (2000)
9. D.L. Tabb, M. Koenig, Infrared Spectroscopic evidence of structural defects in crystalline regions of trans-1, 4 – polychloroprene, J. Polym. Sci.: Polym. Phys. **13**, 1145 (1975)
10. M.I. Boussandel, et al., Radiation Tolerance Assessment of COTS Components for an Optoelectronic System to Measure Polymer Aging in Nuclear Environments, in *2023 RADECS Data Workshop*, Toulouse, France (2023), pp. 1–5
11. G. Repetto, B. Migot, J.-F. Trigeol, V. Soltesz, Viktoria experiments investigating the filtering system in the sump of a PWR after a loss of coolant accident: Part I Physical/chemical effects on strainer head loss evolution, in *NURETH 2019 – 18th International Topical Meeting on Nuclear Reactor Thermal Hydraulics*, Portland, United States (Aug 2019), pp. 407–420

12. T. Druet, A. Recoquillay, B. Chapuis, Passive guided wave tomography for monitoring corrosion in pipes, in *Proc. of the European Conference on NDT*, Lisbon Portugal (2023)
13. P. Calmon, A. Recoquillay, N. Roussel, L. Maurin, T. Druet, G. Laffont, B. Chapuis, Towards passive Fiber Bragg Grating-based measurement of ambient elastic noise for SHM under varying environment, in *Proc. of the International Workshop on SHM*, Stanford USA (2023)
14. R.M. Meyer, L.J. Bond, P. Ramuhalli, Online condition monitoring to enable extended operation of nuclear power plants, in *Progress of Nuclear Safety for Symbiosis and Sustainability*, edited by H. Yoshikawa, Z. Zhang (Springer, Tokyo, 2014) https://doi.org/10.1007/978-4-431-54610-8_17
15. *Buried and underground Piping and Tank Ageing Management for Nuclear Power Plants*, AIEA Nuclear Energy Series No. NP-T-3.20 (October 2018)

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