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REVIEW ARTICLE

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Methodologies for efficient and reliable NPP polymer ageing management

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Abstract. The lifetime of existing Nuclear Power Plants (NPPs) can potentially be extended to between 60 and 80 years if safety and operability of facilities can be guaranteed. This requires efforts in terms of equipment qualification and ageing management to support stakeholders and decision makers. Polymer ageing is of concern due to their widespread use in NPPs (e.g. each NPP contains approximately 1500 km of cables). Predicting their lifetime and monitoring their integrity remain a challenge. Here, we present a cross-cutting review of two on-going Horizon 2020 projects (TeaM Cables and El Peacetolero). The combination of these 2 projects allows to provide the community with non-destructive and predictive tools that can help assess the reliability and functionality of polymer-based components such as cables or pipes. The paper discusses scientific challenges faced in the beginning and achievements made throughout the projects, including the industrial impact and lessons learnt. Two specific aspects highlighted concern the way the projects sought contact with end users and the balance between industrial and academic partners. The paper concludes with an outlook on follow-up issues related to the long-term operation of NPPs.

1 Introduction

The effective maintenance of nuclear power plants (NPPs) is essential for their safe operation. Maintenance ensures that the level of reliability and effectiveness of all safety-relevant components and systems remain in accordance with design assumptions. Scheduling preventive and corrective maintenance operations requires an understanding of ageing mechanisms for different components and materials used in plants, as well as a thorough and quantitative assessment of the health and reliability of safety-relevant components.

The projects addressed in this paper attempt to answer this challenge. TeaM Cables aims to improve the understanding of ageing mechanisms on cables used in plants (specifically to polymers used in cable insulation), to model this ageing mechanism, and to devise NDE and monitoring techniques for health assessment. El Peacetolero aims to set up a miniaturized and portable optoelectronic system able to not only identify a polymer but also determine the degradation level. This equipment, usable by a non-specialized operator or by a remote-controlled device, would allow instantaneous and non-destructive analysis which will increase the reliability and drastically simplify the operations (reducing not only maintenance costs but also an increase in radioprotection).

This paper deals with achievements, challenges and impacts of these projects rather than giving exhaustive descriptions, with the aim to identify potential follow-ups to cover the terrain not dealt with throughout these projects. We therefore restrict the project descriptions to brief portraits in the following paragraphs (Tab. 1).

1.1 TeaM Cables project

TeaM Cables focuses on European tools and methodologies for an efficient ageing management of NPP cables and addresses the challenge of long-term operation for cables – more precisely, their polymer insulation, which is subjected to ageing. The use of numerous cables in a NPP (about 1500 km for one nuclear unit) makes the replacement of cables economically unfeasible, which require accurate predictive models for their safe lifetime as well as for generic tools and methods for on-site monitoring.

TeaM Cables develops a novel multiscale approach for a more precise estimation of the cable lifetime. Cable lifetime is governed by polymer layers' lifetime. A large part of the project is hence dedicated to polymer science. The project analyses the effects of irradiation and

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Table 1. Key figures for projects discussed.

Project	Duration	Funding	Lead	Partners	Framework
TeaM Cables[1]	2017–2022	4,2M€	EDF	13	H2020
El Peacetolero	2020–2023	1,0M€	Sorbonne Université Paris	9	H2020

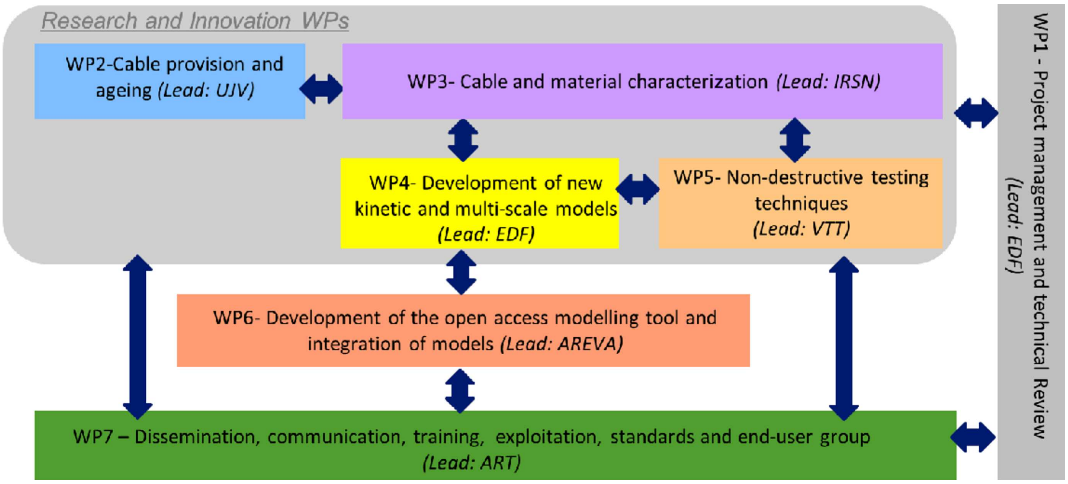

Fig. 1. TeaM Cables work plan.

temperatures on polymers from micro- to macroscale levels, to develop multiscale models of ageing. Ageing in normal operation conditions and accidental conditions will be addressed. The unique multi-scale and kinetic models are integrated into a numerical tool, which will be based on the fusion of a currently used European cable management instrument with a polymer ageing modelling tool. In parallel, criteria and protocols are proposed for on-site use of non-destructive testing techniques.

The programme combines highly scientific work packages for actual polymer ageing kinetics models with experimental work packages to obtain data throughout accelerated ageing (cf. Fig. 1). The consortium is comprised of stakeholders, cable manufacturers, academic partners with specific experience in polymer ageing kinetics modelling, as well as applied institutes for experimental and NDE aspects.

1.2 El Peacetolero project

Polymer ageing control methods are of two types. The first one is the sampling of deposit or real equipment (for example, coring) and subsequently experimental testing of the material in a laboratory. If this method meets the criterion of reliability, this is invasive, expansive, and time-consuming. The second one is the non-destructive exam like indentation. In this case, criteria are based on material-dependent and poorly understood correlations between the measured property and end-of-life criteria. These correlations are material dependent and require previous establishment of relationships between the material's behaviour and environmental conditions. Early detection of abnormal behaviour and embrittlement are therefore impossible with these approaches.

In this respect, El Peacetolero aims to design a TRL 7 hand-held, low power, embedded optoelectronic system that can deploy AI for in-situ real-time measurement, identification and diagnosis of polymers' ageing in an industrial environment. The system performs measurements of material reflectance at specific wavelengths according to InfraRed Attenuated Total Reflectance (IR-ATR). This concept has been recently patented and has been verified and successfully tested by a laboratory prototype (TRL3) [1]. Figure 2 is a block diagram representing an overview of the El-Peacetolero system and its component parts.

The work plan of the project is divided into two distinct large blocks of work as illustrated in Figure 3. The first concerns material's ageing and characterization, data generation and AI and algorithms that will be derived from this for on-site verification. The second one concerns the device itself with the development of the LED and laser heads and the optoelectronics needed. The overall device has been tested, and the results have been compared with "well-known" destructive and other non-destructive methods of characterization.

2 Challenges, achievements, and impact

2.1 Scientific challenges and achievements

TeaM Cables is funded under the framework of the section "Continually improving safety and reliability of Generation II and III reactors" of the Euratom Program 2016 and

[1] Public website: https://www.team-cables.eu/

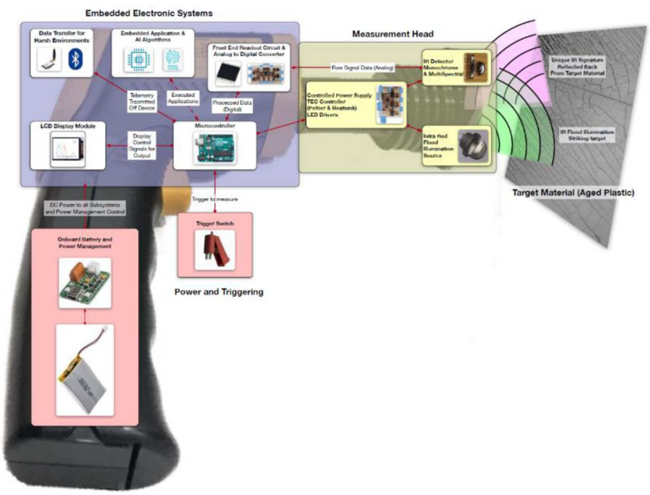

Fig. 2. El-Peacetolero System block diagram.

El-Peacetolero under the framework of the section "Innovation for generation II and III reactors" of the Euratom Program 2019. The main scientific challenge of these two projects is to obtain a deeper understanding of operation-induced degradation mechanisms. This will be notably carried out by developing NDE methods.

TeaM Cables faces multiple scientific challenges related to polymer ageing, which are in part covered by three PhD collaborations with academic partners. The overall ambition of TeaM Cables is to allow NPP operators to improve their capacity to safely manage the lifetime of cables and thereby contribute to ensuring the lifetime extension of NPPs to 60–80 years. To achieve this, a radically new way to predict the lifetime of cables (In terms of mechanical, physical and electrical parameters) is developed, using much more precise information about material composition and more relevant methods for analyzing the data based on multi-scale studies of the materials [2–7].

2.2 Industrial impacts

In a short term, TeaM Cables intends to achieve industrial impact through two end-user workshops, and a closing symposium. Both projects will deliver tools capable of delivering additional substantial information regarding the degradation parameters used for the assessment of lifetime, non-destructively, fast and reducing the material monitoring time. TeaM Cables will organize a training workshop for NPP operators and researchers on the developed tool.

In the medium term, these projects shall provide the background for robust national and EU strategies regarding various polymer components in the field of nuclear reactor safety.

In the long term, results of these projects should strengthen the competitiveness and growth of companies by developing innovations meeting the needs of European and global markets, and notably for El-Peacetolero, by delivering such innovations to the markets. Indeed, the El-Peacetolero tool will be an innovative TRL7 product that will have demonstrated a real use in a safety critical industry. The real-time data that are captured by El-Peacetolero will allow for better scheduling of preventative maintenance and curtail safety issues related to polymer degradation. This will reduce the costs related to shutdowns and will be transferable to many industries where polymer degradation can have implications.

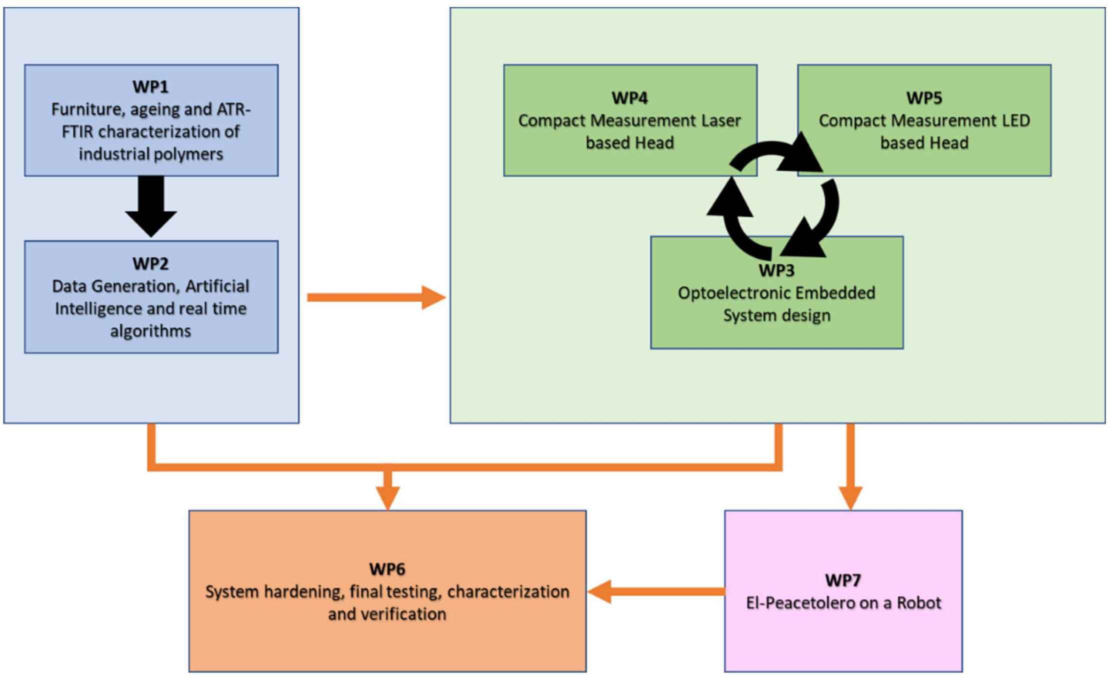

Fig. 3. El-Peacetolero work plan.

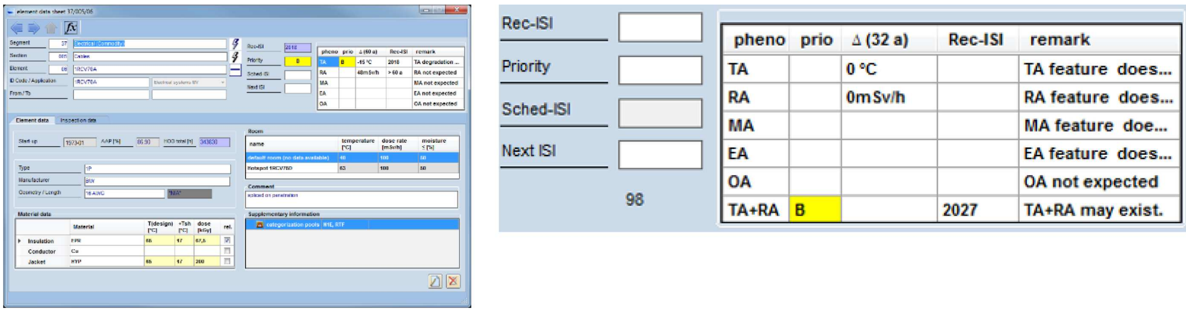

Fig. 4. Component data sheet window (at the left side) and zoom on the evaluation of the duration life of a cable according to the exposure conditions (at the right side).

2.3 End-user's implication

Horizon 2020 focuses on dissemination, which clearly emerges in all ongoing projects. These two projects have designated dissemination work packages.

The El-Peacetolero project will realize a system prototype demonstration in operational environment. EDF engineering is fully integrated into this first demonstration. TeaM Cables involves special task forces providing expert advice on specific R&D related issues and assessing the results, such as materials, methods and tools in nuclear safety measures or S/T advice. These advisory boards are:

- an end-user group: to ensure the industrial applicability of models and tools developed in TeaM Cables. The end-user group members participate in project consortium meetings and in specific end-user workshops dedicated to the assessment of models and tools (Tecnatom, Engie Laborelec, Airbus, Forsmark, Paks II, EDF, NEXANS).
- A technical advisor: appointed by the NUGENIA Executive Committee, he is invited to project consortium meetings and review the deliverables produced by TeaM Cables.
- Advisors on standards: TeaM Cables collaborates with external advisors as Empresarios Agrupados to discuss standardization aspects. They are also invited to project consortium meetings.

To sum up, TeaM Cables pushes this idea particularly far, with a winter school, two end-user workshops, a training workshop for NPP operators and researchers as well as a final symposium.

2.4 Academic involvement

TeaM Cables collaborates with the University of Bologna and ENSAM Paris, with a total of three PhDs. They worked on the development and validation of a kinetics model for polymer ageing, and the use of the output of the kinetics models and multiscale models to predict mechanical, physical and electrical parameters. Three PhD theses are on-going in El-Peacetolero project works with two well-known university Sorbonne Universit Paris (L2E-SU) and Universitat Jaume I (UJI). Their work focuses on the three main scientific areas of the project: the embedded optoelectronic system, artificial intelligence and robotics.

3 Lessons learnt and follow-up issues

One of the challenges concerns the capitalization of achievements made. TeaM Cables realized this already at the proposal stage and centres its capitalization effort around a software tool as a federating item. Indeed, a novel "open access" tool, hereinafter referred to as the "TeaM Cables tool", has been developed integrating the multiscale model and providing the residual lifetime of cables knowing material data and the exposure conditions (wiring network in the NPP). On the one hand, experimental characterizations are carried out at different scales to bring out ageing mechanisms and consequences. On the other hand, models are developed to relate the scales using experimental data as input or validation for modelling. Then, multiscale models have been integrated into the "Virtual Polymer" tool provided by EDF. This tool is then interfaced with some functionalities of the COMSY Cable tool provided by Framatome (cf. Fig. 4).

A first distribution of the TeaM Cables Tool to the partners and end-user group has been recently done. The end-user group is checking the transposability of the models developed on data coming from in-service cables or from databases of previous projects.

To obtain a deeper understanding of operation-induced degradation mechanisms, accelerating ageing campaigns have been performed. Particular attention was paid to maintaining the representativeness of the degradation mechanisms observed under NPP conditions in these two projects. For instance, in El-Peacetolero project, ageing conditions have been chosen to remain as close as possible to the degradation mechanisms involved for pipe applications. Figure 5 shows the dedicated accelerating ageing loop designed within the framework of El-Peacetolero project considering numerous environmental factor (immersion in chlorinated and salted water in temperature).

4 Conclusions

The lifetime of existing NPPs can be potentially extended to between 60 and 80 years if safety and operability of facilities can be guaranteed. This requires efforts in terms of equipment qualification and ageing management to support stakeholders and decision makers. Polymer ageing

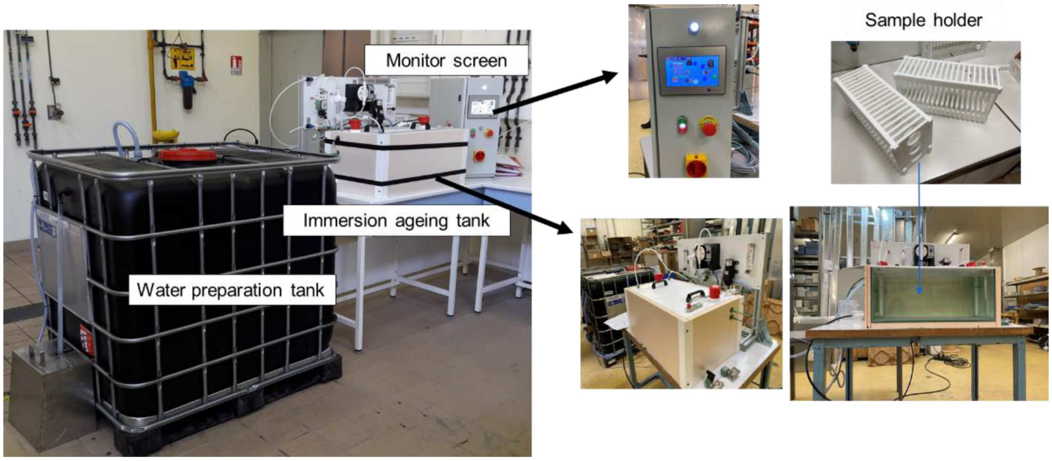

Fig. 5. Design specific accelerated ageing loop.

is of concern due to their widespread use in NPPs (e.g. each NPP contains approximately 1500 km of cables). Predicting their lifetime and monitoring their integrity remain a challenge, which led to the origin of the two ongoing H2020 projects discussed in this paper. The combination of these 2 projects allows to provide the community with non-destructive and predictive tools, that can help assess the reliability and functionality of polymer-based components such as cables or pipes. TeaM Cables not only highlights the importance of ageing models' choice (multiscale approach vs. empirical approach), but also the need to crosscheck the results with data from continuous monitoring and in-service inspections, which allows for predictive maintenance (as opposed to scheduled maintenance).

Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

Data associated with this article cannot be disclosed due to other reasons.

Author contribution statement

Dr. Morgane Broudin is in charge of the overall supervision of the TeaM Cables project as coordinator. Dr. Mohamed Ben Chouikha is the El-Peacetolero project coordinator.

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