33rd International Conference Nuclear Energy for New Europe
NENE 2024
September 9 - 12
PORTOROŽ
SLOVENIA

Map Determination of Code and Standard Needs to be Covered for Innovative Nuclear Reactors

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1 INTRODUCTION

In 2023, the nuclear industry was clearly recognized at international level as having a key role to play in turning the tide on global warming. For the first time, nuclear energy was explicitly mentioned as a solution in the final COP28 declaration and 29 nations have appealed for a common effort to triple nuclear capacity by 2050. In the European Union, for historical reasons, the nuclear reactors still operated today were designed and built using either the US ASME/ASCE Codes, European codes (AFCEN for France, KTA for Germany), Russian codes (PNAE G-7), or even a mixture of codes adapted at a national level. This led to a European nuclear reactors fleet built with a "patchwork" of reference codes, leading in some cases to higher costs for spare parts and to a more complex follow-up of activities. As of 2017 and mentioned by the EC Directorate-General "Energy" in its Nuclear Illustrative Programme [1], this situation is hampering the competitiveness of the nuclear industry and therefore the deployment of new capacities. It is expected that the authors will submit carefully written and proofread material. Spelling and grammatical errors, as well as language usage problems, are not acceptable. The authors should limit their papers to 8 pages, presenting their results as concisely as possible.

Nuclear energy allows to provide low-carbon and plannable electricity. Moreover, nuclear will also produce industrial heat. To achieve the reduction of global greenhouse gas emissions, and the goal of decarbonisation by 2050, new light-water reactors of Generation III are needed to be constructed, as well as more innovative «non LWR» Generation IV reactors (Advanced Modular Reactors - AMR), with a generic trend, concerning the size, for Small Modular Reactors (SMR) which should take an increasing part. The large number of nuclear projects calls for harmonisation. Indeed, the business model for this type of reactor relies on above all modular design with smaller components produced in large series and with large-scale deployment in several countries.

The HARMONISE project [2] is a research and development initiative supported by Horizon Europe which aims to accelerate the implementation of innovative nuclear technologies, to identify the gaps that need to be filled to favour the licensing of those technologies under development and which could contribute to the European energy mix in the short/medium term.

HARMONISE project will propose approaches on how the codes and standards applied in the field of fission and fusion power could be harmonized and how the licensing processes and approaches could be made clearer and efficient. Such harmonization will help to improve the public perception of nuclear energy in general and, in particular for the first-of-a-kind innovative nuclear designs.

2 WORK PACKAGE 4 : CODES AND STANDARDS NEEDS FOR INNOVATIVE NUCLEAR POWER PLANTS PAPER FORMAT

HARMONISE WP4 focuses on codes and standards. Innovative reactor projects call for new technologies and new materials, different operating conditions from existing reactors or special component designs. These three aspects give rise to new needs in terms of codes and standards. The work scheduled s part of this project consists, first and foremost, in identifying these needs, task 4.1 (Figure 1). To reach our target, initial data were collected from project partners involved in innovative reactor projects such as DEMO (a large power Fusion Reactor) and ALFRED (Lead Fast Reactor), and a questionnaire was sent to reactor projects, including many start-ups that have been created in the recent years.

These needs are collected from questionnaire that will be sent to the Standard Development Organisations (SDOs), task 4.2 (Figure 1) which are expected to assess and provide methodologies. In parallel, the questionnaire will also be sent to other industrial sectors such as aerospace, automotive, rail, etc... To take into account how new technologies (essentially digital and manufacturing technologies) have been taken into account and in investigating the possibility to transfer this to nuclear realm the codes and standards rules successfully developed by other industries. The uniform outlook will help the reader to follow the proceedings. This can be obtained most easily if the authors use this template file to construct their manuscripts. Please note the following details: this template is an A4 format with 25 mm margins on the left, right, top and bottom.

As a key output, a map will be produced; it will describe the evolution of the codes and standards to fill the gaps and address the development needs. Implementation of solutions will be conducted under task 4.3 (Figure 1).Particular attention will be given to the identification of potential improvements in the harmonisation of codes and standards that could be adopted to support deployment of innovative reactors with respect to overall cost reduction and nuclear safety.

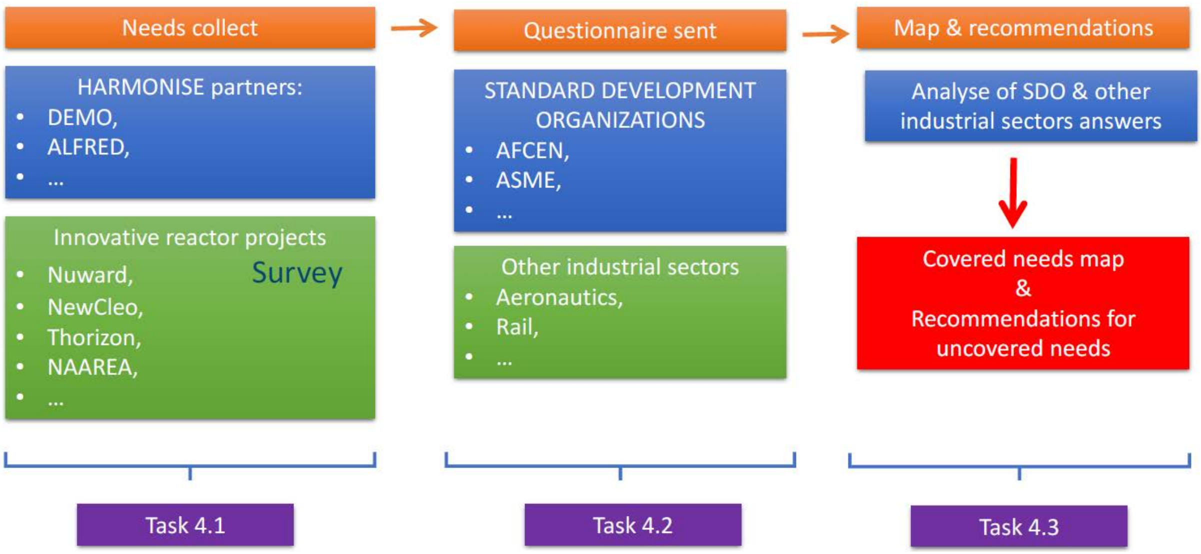

Figure 1 – WP4 Content and Task

Before addressing the WP4 process, relevant stakeholders have been identified including relevant Standardisation Development Organisations. A deliverable provides a comprehensive list of the relevant stakeholders [3] for the project and establishes the suitable means of communication with them, offering the possibility to express and communicate their positions, views and visions on the technical opportunities and challenges expected to be faced as a result of adopting a technology independent (performance based) regulation framework for nuclear facilities.

3 WP4 TASK 4.1 – NEEDS COLLECT SUBMITTING THE MANUSCRIPT

The first stage of WP4 consisted in collecting Codes and Standard needs for innovative reactors. In recent years, innovative reactor projects have been emerging, mainly SMR (essentially PWR-type reactor) and AMR projects. The IAEA has listed these projects in its ARIS database [4]. More recently, in France, as part of the "France 2030" call for projects [5], the government launched an "Innovative Nuclear Reactors" section in 2023, which resulted in a number of new start-ups for different innovative reactor concepts. The needs can be split into two main categories: i) new designs with more challenging operational conditions and with much less, or no feedback experience; ii) the need to incorporate new materials, new manufacturing methods and digital technologies.

The innovative reactors include a wide range of 4th generation technologies [6] - the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very high-temperature reactor (VHTR) - and also fusion reactors. These reactor concepts, which are not new, but are nonetheless being revisited as they have better long-term sustainability. More stringent safety and cost management require innovative components (for example, for the MSR, core internals providing greater resistance to salt corrosion to ensure a service life of 60 years) and/or because of the unusual size envisaged.

The successful deployment will also rely on the adaptation of new technologies: manufacturing processes, e.g. additive manufacturing, non-destructive evaluation or repair processes.. To ensure the fastest possible development of their reactors, start-ups will also need to incorporate the most advanced digital technologies, such as digital twins, artificial intelligence, wireless applications, etc…

The methodology involved the development of a "capture matrix" to systematically gather input related to technology gaps. It was designed to ensure comprehensive coverage of the required information and facilitate the organization of data in a clear and systematic manner. The capture matrix was shared with experts participating in the task as well as external stakeholders covering a wide range of innovative nuclear technologies. The entries of the matrix are the following:

- Type of power plant: Type of plant (fusion or fission power) should be specified. In the case of fission, the generation of the power plant (III+, SMR, Gen-IV, others) should be indicated.
- Type of technology: For fusion, the specific concept (e.g., tokamak, stellarator) should be specified. For fission, the technology (e.g., LWR, LFR, etc.) or any other relevant classification should be specified.
- Structure, System, and Component: The specific innovative component under consideration should be identified. Materials: The materials used for the Structure, System, or Component (SSC) in question should be specified.
- Topic: The challenges involved, such as design, inspection, maintenance, or coding of new materials, should be described.
- Due by (anticipated date of need): The year by which the topic is expected to be addressed, including the establishment of recognized guidelines and criteria should be indicated.
- Life cycle phase: The topic should be associated with a particular phase in the life cycle, such as design, manufacturing, construction, operation, or decommissioning.
- Existing standard and code availability or requirement: The situation whether there is an existing code that needs modifications or if an entirely new set of guidelines and criteria is necessary should be specified.
- If existing code or standard are available, specifies: In the case of an available existing code, the code should be clearly specified, mentioning also if the is including guidelines and criteria relevant to the topic of interest.

For digital needs, supplementary entries are:

- Application: The concerned field should be specified, as safety demonstrations, planning/support of supervision/maintenance, optimize plant operation, work planning, etc …
- Implementation: tools that should be implemented as digital twin of the plant/of systems, AI supported/enhanced simulation tools for material properties/mechanical engineering/thermal hydraulics engineering, etc …

3.1 Codes and standards needs [7]

The activity received feedback from 10 organizations (including external stakeholders) representing most of technologies under development in Europe (water cooled SMR, AMR and fusion plants).

For code and standard needs, survey results can be seen on figure 2 on which needs have been arranged by main topic. The survey revealed the following needs from most of the developers [7]:

1. To extend the applicability of existing materials to operating conditions broader than the current ones in terms of temperature and dose rate. Examples of these materials are the austenitic steel family: 316, 316L, 316L(N) or 15-15Ti (AIM1).
2. Qualification (production and properties) and codification of innovative materials in codes and standards in support of design of systems and components. Examples of these materials are AFA steels, Eurofer, CrCuZr or MAXTHAL.

3. Development of codes and guidelines for the use of corrosion protection coatings, including acceptable coating process, requirements and objectives for pre-service and In-service inspection.
4. Development of compatibility guidelines between structural materials and innovative coolants (especially liquid metals).
5. Qualification and codification of innovative processes such as additive manufacturing.
6. Implementation of criteria and requirements for non-destructive techniques adapted to the new types of reactors, components and manufacturing techniques.

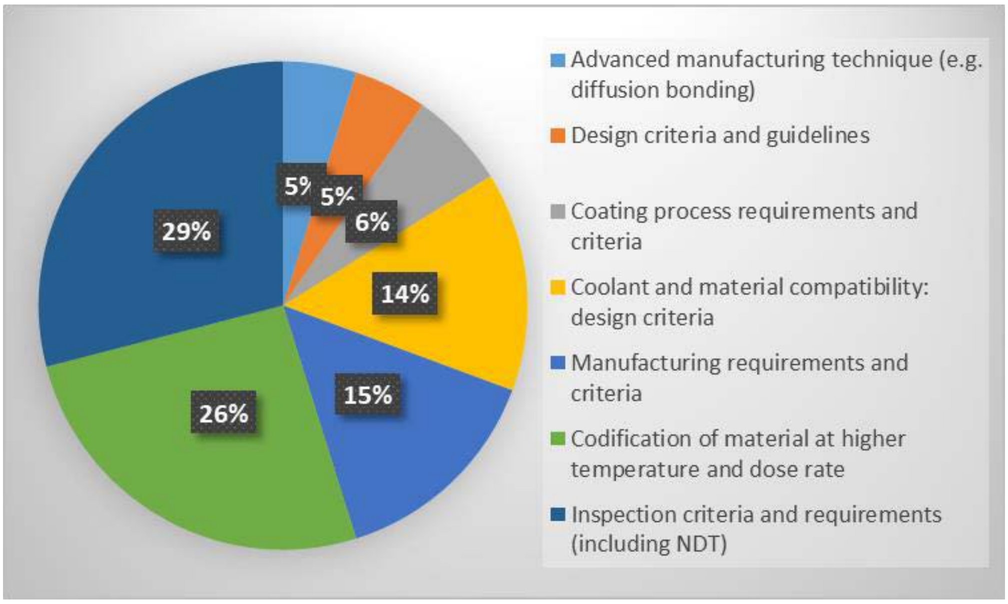

Figure 2 - Map of Topics requiring C&S from Project partners

The coding requirements cover all the main reactor components, i.e. the reactor vessel, internals, steam generators, primary pumps and fuel cladding.

The need for codification of materials arises from different operating conditions that require the qualification range of existing materials to be extended (e.g. higher temperature or higher irradiation dose) and/or qualification of new materials and advanced manufacturing methods to be introduced. In the latter case is the traditional approach was 'simply' a matter of introducing a new grade of metallic material (e.g. Inconel 625), which will require mechanical testing campaigns to determine the material data.

To meet more stringent operating conditions, new materials are required, SiC ceramics as example, either in the form of solid material or composites. Before determining the material data, it is necessary to define the mechanical strength rules for materials characterised, for example, by brittle behaviour.

For MSR, ADS and LFR, the challenge is to guarantee the long-term corrosion resistance of the core materials to molten salts, LBE or liquid lead respectively. This can be achieved with a single structural material or with a coating. In both cases, a qualification method must be established for long-term corrosion resistance. For coatings, the qualification also covers the manufacturing process.

Any material or component qualification will rely on experimental testing, but to accelerate the process traditional tests well need to be complemented by accelerated tests and integration with modelling an and digital technologies.

New component designs are leading to the development of new in-service inspection methods using new non-destructive testing methods. Here again, the question of qualification arises.

3.2 Digital needs [8]

Due to the limited received inputs for selecting digital technologies to be covered by this task of WP 4, the investigation on technologies was concentrated on those which were mentioned in the survey of stakeholders of the HARMONISE project and which are covered by the open literature [9]. Therefore, three main technology areas were selected: Artificial intelligence (AI)/machine learning (ML) [10], digital twins (DT) and augmented/virtual reality (AR or VR).

Among the technologies mentioned in the survey answer, AI/ML was covered in as was advanced human machine interfaces (especially augmented reality and virtual reality) and digital twins (including virtual sensors, materials and plant models during design and operation, “bookkeeping” of events and their effect on aging ("Comptabilisation des situations digitales")). In the survey answer cybersecurity was mentioned. This topic was not further investigated, as security topic was out of the scope of the HARMONISE project.

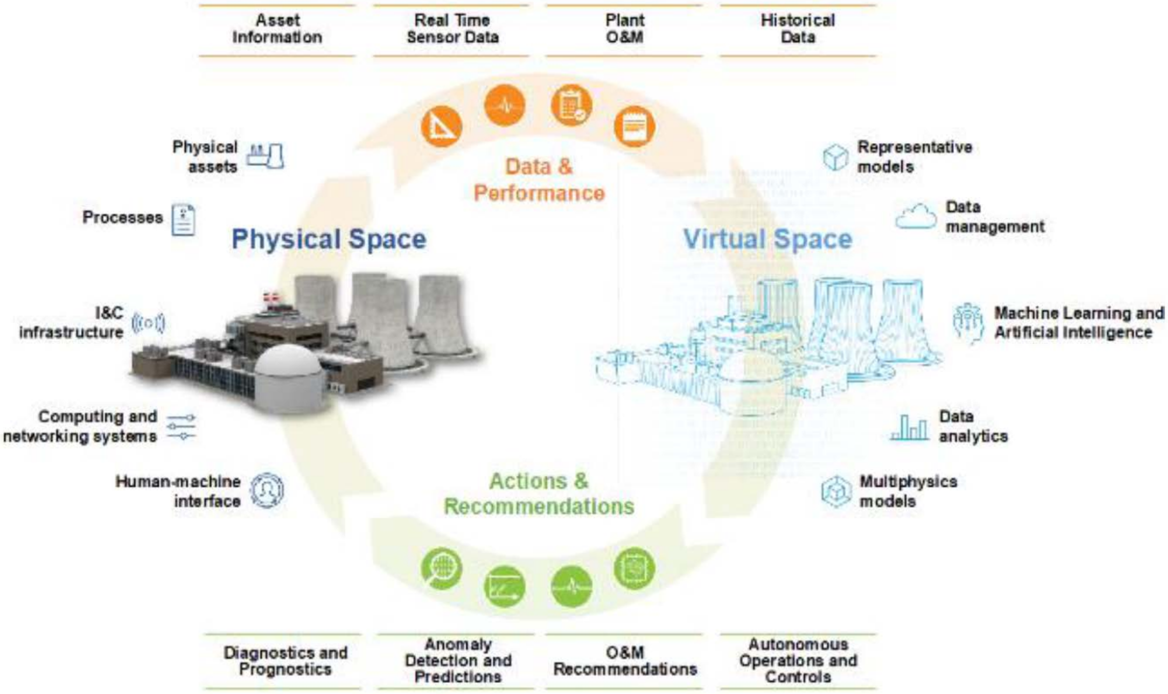

Figure 3 Digital Twin for NPP [12]

A Nuclear Power Plant (NPP) specifies an integrated nuclear digital environment that would contain a chain of interconnected data from physics simulations, in-service monitoring, and plant inspections. Some basic elements are mentioned: monitoring systems, advanced modelling and simulation, data analytics, data repository, and DT platform and integration systems [11].

As shown on figure 3 and 4, the main benefits of implementing DTs are related to:

- enable real-time data exchange and provide the ability for smarter and more informed decision making ;
- track and manage the nuclear power plant lifecycle from construction to operation, to license extension and beyond, to minimize cost, increase efficiency and ensure the availability of long-term safe and reliable energy ;
- enhance inspection activities, including automated regulatory compliance testing and on-demand access to high-fidelity plant information.

Based on their current use, it may be estimated that the digital twins may be successfully applied for: plant-simulators; condition monitoring; failure and degradation prediction; predictive maintenance; analysis of operational plant data; design and prototype development.

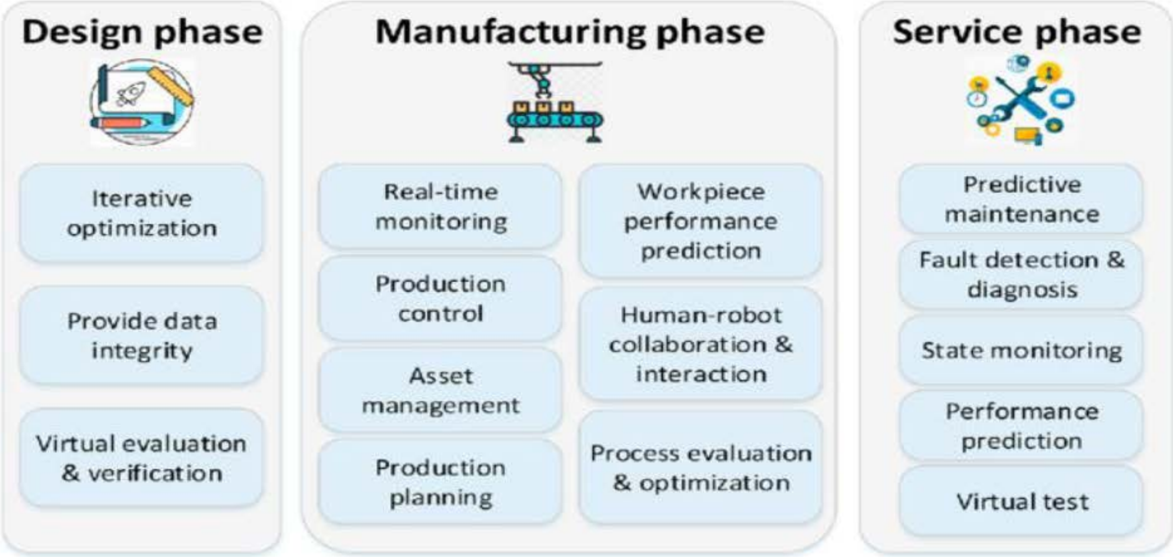

Figure 4 DT benefit for NPP life stages [13]

Because the application of DT-enabling technology is likely to be a potentially asset for long-term viability of currently operating reactors, identifying and addressing the challenges and gaps associated with DT-enabling technologies is an important step toward preparing its implementation. Such advancements may feature integrated digital technology, more fully instrumented plants, improved plant information and control systems, and advanced operations and maintenance practices, all of which may be integrated within a DT system.

The main motivation for augmented/virtual reality (AR or VR) was identified as the possibility for the user to experience situations beyond what is possible in the real world, e.g. accident events [9]. Possible future applications for AR/VR could be found during design of plants, during operation of a plant, e.g. to increase workers' awareness of local high-dose rates, or to assist plant health monitoring und inspection. Already now, AR/VR is used for work planning and for training. The main challenges for the application of AR/VR in the nuclear sector is the need to demonstrate the correctness of the visualized "reality" and its agreement with the state of the real plant [14]. This is of utmost importance, if the health or life of plant works depend on the visualized information, e.g. about the local dose rate.

Demonstrating compliance with high-level regulatory requirements for nuclear power plants is a challenge for any use case with an impact on safety. In addition, the interfaces to security and safeguards will have to be considered. Particularly challenging will be safety demonstrations where a high degree of reliability needs to be demonstrated. There is a lack of specific regulatory guidance on how to meet expectations for the safety demonstration related to use cases of AI and ML, DT, and AR/VR in nuclear. Achieving common regulatory positions on these issues will be a high priority.

4 CONCLUSIONS

The objective of the Task 4.2 is to evaluate to which extent existing codes and standards fulfil the needs of innovative nuclear projects (identified in the Task 4.1). For codes and standards this will be done through a survey that will be sent to Standard Development Organisations (SDOs). The survey will also be sent to other industrial sectors than nuclear. Indeed, the use of new technologies under controlled conditions is a generic problem for all industrial sectors. It is therefore relevant to look at how other industrial sectors have or will integrate these technologies from a regulatory point of view. It will then be up to see whether it is possible to transfer the solutions implemented elsewhere to the nuclear sector, with any necessary adaptations.

From the data provided from the answers of the questionnaire, a map of the needs will be drawn up already covered, or not, in existing codes and standards. For the needs that are not covered, HARMONISE will provide recommendations to solve the gaps. At the same time, we are calling on the other industrial sectors and we will study the possibility of taking benefit (with the necessary adaptations) in the nuclear field from the solutions implemented by these sectors.

A map will be formulated describing the evolution of the codes and standards to fill the gaps and address the development needs be identified in the task 4.1 entitled “Needs collect”. Emphasis will be placed on identifying potential improvements in the harmonisation codes and standards that could be adopted when the proposed innovations are implemented.

ACKNOWLEDGMENTS

This project has received funding from the European Commission – Euratom under Grant Agreement No 101061643. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or European Commission – Euratom. Neither the European Union nor the granting authority can be held responsible for them.The organizer gratefully acknowledges the work done by all Organizing Committees of the International Conferences Nuclear Energy for New Europe who prepared the first and the improved versions of the template.

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