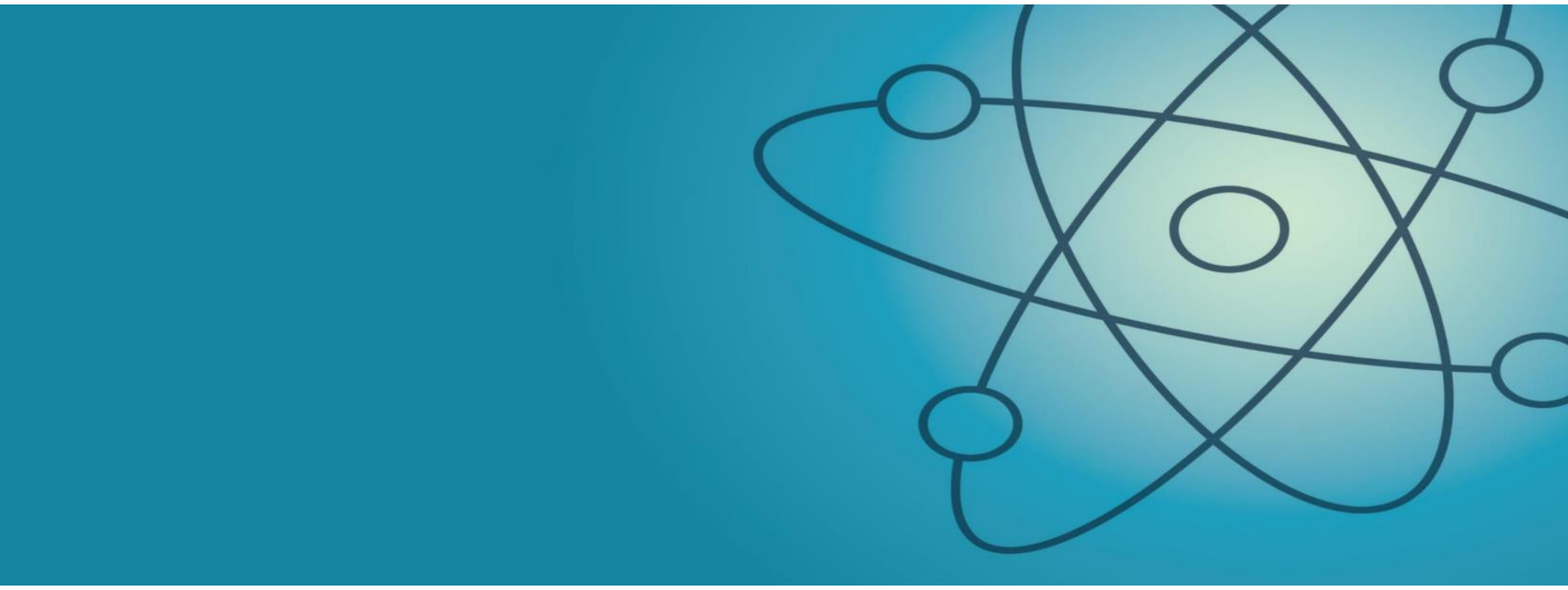

European SMR pre-Partnership Reports

Workstream 5 –

Research, Development, and Innovation Roadmap

SMR European pre-Partnership

Workstream 5

R&D&I Roadmap

Contents

ACRONYMS

Abbreviation	***Expansion***
AMR	Advanced Modular Reactor
ALARA	As low as reasonably achievable
BWR	Boiling Water Reactor
CHF	Critical Heat Flux
CHP	Cogeneration of Heat and Power
CRDM	Control Rod Drive Mechanism
DBC	Design basis condition
DEC	Design extension conditions
ESNII	European Sustainable Nuclear Industrial Initiative
FIV	Flow-induced vibration
HTGR	High Temperature Gas Reactor
HTR	High Temperature Reactor
IASCC	Irradiation-Assisted Stress Corrosion Cracking
IAC	Irradiation Assisted Corrosion
IET	Integral Effects Test
IGSCC	Intergranular stress corrosion cracking
ISI	In-Service Inspection
LBE	Lead-Bismuth Eutectic
LCOE	Levelized Cost Of Electricity
LFR	Lead-cooled Fast Reactor
LW-SMR	Light Water Small Modular Reactor
MSR	Molten Salt Reactor
NDE	Non Destructive Evaluation
NDT	Non-destructive testing
NC2I	Nuclear Cogeneration Industrial Initiative
NPP	Nuclear Power Plant
NSSS	Nuclear steam supply system
PWR	Pressurized Water Reactor
PSA	Probabilistic Safety Assessment
R&D&I	Research & Development & Innovation
REPAS	REliability of PAssive Systems
RMPS	Reliability Methods for Passive Safety
RPV	Reactor pressure vessel
SET	Separate Effect Test
SFR	Sodium-cooled fast reactor
SG	Steam Generator
SMR	Small Modular Reactor
SNETP	The Sustainable Nuclear Energy Technology Platform
SSCs	Structures Systems and Components
TRISO	TRi-structural ISOtropic particle fuel
TRL	Technology Readiness Level
WS	Workstream

1. GENERAL CONTEXT AND OBJECTIVES OF WORKSTREAM 5

SMR technologies have a great potential to play an instrumental role in the European ambitious environmental and energy sovereignty challenges. In the wake of the huge potential market opportunities associated with the decarbonization of our economies, many players outside and inside the European Union are active in bringing these technologies to reality in Europe.

The primary objective of WS5 is to define an **R&D&I program** consistent with the European **market needs** and the **licensing requirements**, to ensure the implementation of the highest nuclear safety standards in Europe and secure a best-in-class position for European industry and R&D organizations within the international competition, and eventually set enabling factors towards an industrial demonstration of these low carbon technologies in the EU.

To roll out such program, WS5 also aims at identifying the needed **facilities** to perform these R&D activities, and at setting up a coherent and consistent **training and education program**.

The R&D challenges to support this ambition are numerous, and the depth of the associated R&D gaps directly depend at the first order on the basic fission technologies (coolant, moderator, fuel) selected by each SMR vendor.

With this respect and in the light of the diversity of technological maturities between all the SMR models currently being developed, two parallel approaches have been retained by the WS5 participants.

The first approach is to primarily focus on the technologies which are credible for a first commercial operation in the 2030s that are the **LW-SMRs**. The maturity and the accumulated operational experience of the LW-SMR technologies are unequaled. The R&D&I roadmap for these technologies thus outlines a closer to commercial deployment, with shorter-term objectives.

The second approach is to seek for a **sustainable** use of the nuclear energy in the longer run. In this regard, specific R&D streams for Advanced Modular Reactors (**AMR**) are also to be reinforced now. AMR come along with Generation IV features. Some of the AMR select fast neutron technologies, making it possible to close the nuclear fuel cycle, pursuing to limit and eventually get rid of mining new raw material (natural uranium), and/or having the potential to limit the impact of the nuclear long-life waste by increasing the recycling potential of the fuel. AMR also generally often operate at higher temperatures than LW-SMR, which opens the perspective to a deeper decarbonization potential of industrial needs.

The fundamentals of this European R&D&I program are to bring elements that will demonstrate the level of safety, performance, and cost-effectiveness (especially including the industrial mastery and capability to execute projects rapidly and efficiently) of the SMR technologies.

The first activity of the WS5 in 2022 was thus to share a common view on technical/scientific hurdles that are generic to SMRs. The R&D gaps discussed may thus exclude very specific needs of individual reactors design, but shall form a comprehensive roadmap leading to:

- Accelerating the R&D towards LW-SMR operation in Europe
- Complementing the expected demonstration of the safety and performance of SMR in Europe
- Demonstrating the benefit and feasibility of innovations of specific interests for SMR
- Exploring new uses / new rendered services, one objective being the possibility for AMR technologies to emerge and to be in position to make an informed selection on the reactor technology and design options in the mid-term for a fully mature industrial AMR wide deployment in the second half of the century.

WS5 activities have been launched under the umbrella of SNETP, and the workstream benefited from the contribution from various EU players (see Appendix A). The contributors agreed to develop the roadmap according to seven topics, listed below:

1. Core and fuel, including the control rod drive line
2. Nuclear Steam Supply System (NSSS) components, especially the integrated vessel and its internals
3. Passive systems

4. Severe Accidents
5. Modularity
6. Human Factors
7. Uses beyond electricity

This work benefited from common and shared starting points, which are the *SNETP strategic research and innovation agenda* issued in July 2021, and the ongoing Euratom Research projects related to SMR technologies [1] as illustrated in the table below (the list is not exhaustive).

The first difficulties faced for each topic were the heterogeneity of the needs for the technologies of interest, the capability to identify R&D gaps while staying generic and technology neutral. The articulation between LW-SMR and AMR, the link with existing LW-SMR vendors' specific R&D programs, and the links with some key LW-SMR related Euratom projects is summarized in the table below.

Table 1. Articulation between LW-SMR and AMR, link with LW-SMR vendors' R&D programs, and existing LW-SMR Euratom Research projects

R&D&I topic	LW-SMR / AMR	LW-SMR vendors' R&D Programs	Link with LW-SMR Euratom projects
Transverse	Common (structuring safety objectives)		ELSMOR Towards European Licensing of Small Modular Reactors [2]
Core / fuel	LW-SMR then AMR	Very specific to design options and to reactor technologies	
NSSS vessel	Common topics on ISI, advance manufacturing	Very specific due to technologies or designs choices (materials, components manufacturability and performance), but could benefit from generic manufacturing alternatives in the mid-term	NUCOBAM [3]
Passive systems	Common	Specific integral effect tests (IET), but some separate effect tests (SET) may be generic, and a generic IET may be of interest for agreed upon methodologies and generic tests	PASTELS [4] ELSMOR Towards European Licensing of Small Modular Reactors
Severe Accidents	LW-SMR then AMR	LW-SMR generic R&D proposals mostly covered by SASPAM-SA or specific to regulatory framework	SASPAM-SA [5]
Modularity	Common	Depend on the vendors approaches	
Human factors	Common	To be demonstrated for each project, but some shared evidence would contribute to acceptability	
Uses beyond electricity	Common, but specificities exist for technical coupling of the nuclear heat	Dependent on projects, but safety and acceptability aspects to be anticipated may be common	TANDEM [6]

The WS5 participants developed preliminary R&D&I program orientations which are developed in the following chapters of this report.

Especially for the topics related to passive systems, severe accidents, and human factors, WS5 members sought in 2022 to get concurrence of the licensing workstream (WS2) on these key items with the objective to:

- Have a clear view on the level of harmonization (on the licensing process, on safety objectives) among European Regulatory Bodies, to facilitate the design development of innovative reactors that could in the end meet national regulatory requirements.
- Be in position to propose robust SMR designs, that would accommodate a large number of various national regulatory expectations and interpretations.

Four designs of LW-SMR are being considered by various stakeholders (member states, intensive users, industries, …) in Europe: Nuward SMR [7] being developed under the leadership of EDF (France), BWRX-300 [8] developed by GE-Hitachi's (USA-Japan), VOYGR [9] by the start-up Nuscale (USA), and Rolls-Royce [10] SMR in the UK. In addition, new European designs have emerged recently such as the LDR-50 [11] developed by VTT (Finland) that are dedicated, exclusively, to district heating. This R&D&I roadmap could be consolidated in a further revision considering interviews with specific LW-SMR designs of interest, to make sure that it is consistent with their own R&D program, and that it provides a comprehensive and coherent complement to the already launched R&D programs of the designs selected in the Partnership.

Concerning AMR, due to the wide diversity of the technologies and designs being developed, it was found difficult to develop a specific R&D&I roadmap, therefore WS5 took stock from the R&D&I program visions shared in the *ESNII* vision [12], the *NC2I* roadmap [13] issued by the SNETP, and by the Generation IV Initiative Forum [14]. The AMR technologies which have the most active R&D in the EU are: LFR (Lead Fast reactors) or SFR (Sodium Fast Reactors); HTGR (High Temperature Gas-cooled Reactors); and MSR (Molten Salt fast Reactors).

Besides, this first version outlines the need to further develop appropriate enablers at the European level such as: computer simulation codes, digital twins, robotics, artificial intelligence technologies, advanced materials, … that are considered as essential innovation fields of benefit to the EU-industry and society at large as well as to the nuclear sector in particular.

In addition, effort has been dedicated to identifying the needed of experimental infrastructures to roll out this program. Although the list is still preliminary; it appears already clearly that the maintenance of the existing and further development of new ones is key not only for the test, demonstration, and qualification of innovative technologies but also for the education and training in Europe. Emphasis is made especially on the need of Material Testing Reactors and irradiation facilities (cf. AMR), large scale thermal-hydraulics test facilities, and demonstration prototypes for the integration of SMRs into an energy mix.

Finally, in the coming phase, the R&D&I program should be complemented with insights from designers/licensees selected by the European SMR Partnership and confronted with the vision of a network of EU R&D facilities. This work will also allow to set a timeline associated with the R&D&I actions.

In the following chapters, the R&D gaps and needs as well as the associated R&D infrastructures will be detailed for each of the seven topics identified above.

2. CORE AND FUEL

2.1. R&D gaps

Regarding core design and fuel, SMRs can be split into two main categories (independently of a specific design), depending on the operational technologies (coolant, moderator, …):

- Light Water reactors (LW-SMRs) are part of Gen-III class of nuclear reactors, that is a well-known, robust and safe technology, that can allow for rapid licensing of concepts, and for which reactors can be deployed as early as 2030's;
- The second includes all other concepts that do not use light water, they are classified as Advanced Modular Reactors (AMR), which would make it possible to achieve higher levels of performance (particularly with regard to fuel recycling and/or medium/high-temperature energy uses) and safety, but for which more R&D work remains to be done.

The commonalities of each of these 2 categories are being considered and the main gaps have been identified:

For power generating LW-SMRs (electricity & cogeneration), the main gaps concern:

- Since SMR cores are smaller, neutron leakage is proportionally more important than in large-scale reactors, which detrimentally affects their cycle length and average discharged burnups, thus their LCOE. Neutronic improvements shall be contemplated to overcome these disadvantages, like:
    - Fuel assembly design with improved moderation, for instance 16x16 instead of 17x17;
    - Neutronic reflector with new design or material at the periphery of the core;
    - Use of alternative reactivity control systems like drums located at the core periphery.
- Some designers are developing cores without any soluble boron. This design strategy makes some accidents impossible to occur (boron dilution) and simplifies the support systems. However, with such cores, some issues are raising, concerning the local power peak factors that need to be improved, which are being addressed according to dedicated R&D actions, such as:
    - Use of burnable poisons beyond the current PWR qualification domain, like Gadolinium at high content or like Erbium;
    - Long-term insertion of control rods within the core (evolution of the absorbers and surrounding fuels in neutron flux, maneuverability, power peak factor).
- LW-SMR designers plan to use off-the-shelf uranium oxide (UO_2) pellets already widely used for the large power light water reactors already in operation (LEU, low enriched uranium, that is enriched with uranium-235 up to 5%). This allows to facilitate the licensing process, and to enable the deployment of the first series of SMR in the 2030s, using already existing supply chains and technologies. However, SMR should also benefit from fuel evolution, like accident tolerant fuels (ATF), which have the potential to enhance safety.
- Regarding core thermal-hydraulic design, SMRs have smaller cores than large PWRs, and their fuels are shorter, typically half the height of usual fuel assemblies. Heated length may affect the thermal-hydraulic behavior and requires determining the critical heat flux (CHF) performance. CHF is one of the key limiting parameters for normal operation and abnormal anticipated operational occurrences (AOO), related to the first safety barrier integrity. CHF performance evaluation is primarily established on experimental data which are practically non-existent in open form for this type of geometries.
- Both fuel and cladding limits and safety rules should be accurately investigated regarding two aspects:
    - The consequences of additional maneuverability/flexibility requirements, due to the expected substantial share of variable energy sources (wind, solar) in the electricity mix, or due to the cogeneration mode (different demands);
    - The consequences of smaller core design towards neutronic axial and radial edge effects.
- The monitoring of the main core thermal-hydraulic/neutronic/radiologic conditions during reactor functioning through implementation of in-core dedicated instrumentation should be evaluated in the case of smaller and more compact core/vessel design.
- The development of best-estimate approaches for reactor and fuel studies is needed to remove some conservatism for the benefit of design and cost margins. In this framework, innovative multiphysics and multiscale modelling and simulations must be implemented, while considering their V&V (Verification and Validation) issues.

For LW-SMRs dedicated to District Heating, which would operate at low pressure and low temperature (recent networks operate at 70°C, which induces core temperatures of about 170°C and pressures around 15 bars), several gaps have been identified:

- Fuel qualification (both UO_2 pellets and cladding) at low temperature and pressure;
- Reactivity feedbacks for core driving;
- Core sensitivity to specific transients;
- Validation of thermal-hydraulic models at low pressure (higher ranges of void fraction).

For LW-SMRs, the afore mentioned R&D topics will contribute to increase the core designs maturity with possibly improved assemblies, new burnable poisons, new control rod mechanisms with innovative means of driving small cores without soluble boron and with extended fuel and core qualification.

Concerning the second category, 4 concepts (HTGR, LFR, SFR, MSR) have been investigated within the EU since the 1980's. The R&D gaps concerning the core design and the associated fuel types can be summarized as follows:

Concerning modular HTGRs – which offer the ability to release the decay heat by intrinsic properties of the core & reactor – two main gaps are identified:

- European fuel manufacturing process: kernels, coating, compacts/pebbles;
- Development of NDE techniques for quality control of TRISO fuel.

Some other gaps are relevant to mention:

- Check the validation of core analysis tools;
- Development and qualification of a fuel performance code.

Most of Advanced Modular Reactors (AMR) designers are developing reactors requiring High-Assay Low-Enriched Uranium (HALEU), that is uranium fuel enriched between 5% and 20%. This type of fuel makes it possible to achieve smaller designs, longer reactor core cycles, and increased efficiencies. However, since operation experience feedback for such fuel is missing, fuel fabrication and fuel reprocessing capabilities needs to be demonstrated, in parallel of developing the associated supply chain.

In the SNETP framework, the sustainability of the fuel cycle is one of the main objectives (better use of natural resources and minimization of high-level waste through a closed fuel cycle). Therefore, the focus has been devoted to the two technologies that are the most supported in Europe: **sodium and lead fast reactors**. Thus, the main gaps associated with this type of reactor are linked to the small size:

- Fuel qualification at higher enrichment (Pu/U ratios);
- Manufacturability constraints and related qualifications (e.g., higher pin diameter than typical);
- Fuel qualification at lower power ratings than those substantiating the available qualification domain;
- Development of alternative fuels to MOX (e.g., nitrides).

Finally, some AMR rely instead on the **Molten salts reactors (MSR)** technology and are anticipated for a significantly longer-term deployment chiefly because of the very limited operational experience available. The most remarkable gaps identified for the core/fuel of this kind of reactors are:

- Data acquisition on the fuel molten salt properties;
- Development and qualification of control and shutdown means;
- Qualification of the core neutronics, including reactivity feedbacks and kinetics, being inherently coupled with thermal-hydraulics;
- Development and qualification of on-line fuel reprocessing (as one of the key claims for closing the fuel cycle in-the-box) and fission products management.

2.2. R&D infrastructure

Concerning LW-SMRs technology, several existing R&D facilities can be used, as for:

- burnable poisons qualification, the required R&D facilities are experimental reactors (Belgian Reactor 2 BR2 [15] and Petten High Flux Reactor HFR[16]);
- fuel thermal-hydraulics qualification, several facilities are of interest to perform critical heat flux evaluation (KATHY loop in Karlstein Framatome [17], ODEN loop (Westinghouse Electric Co Sweden) [18] and to validate the new control rod technology (HERMES-P of CEA in Cadarache [19], KOPRA loop of Framatome[20]).

3. NSSS VESSEL AND ITS INTERNALS

Most LW-SMR designs that are currently under development are integral PWRs, which due to their design (virtually the complete NSSS fully embedded in a relatively compact metallic containment vessel) exhibit a number of technical challenges related to the NSSS that need to be resolved for deployment of LW-SMRs.

In general, SMRs technologies, and especially AMRs such as Fast Liquid Metal Cooled Reactors - require the development of innovative materials and components for a competitive and safe operation, throughout the life cycle of the plant.

3.1. R&D gaps

Reactor internal hydraulics (incl. vibration)

Thermal Hydraulics of LW SMR will be similar to the one of large LWRs. However, given the different size of components, the scale and importance of relevant phenomena (e.g.: subcooled boiling, CHF onset, flow instabilities, induced vibrations, natural circulation) may be different.

The large number of studies performed on thermal hydraulics of LWRs in the past represents a valuable asset and reference to identify the relevant correlations and predict the most relevant phenomena.

The existing qualified codes for thermal hydraulics analysis can be used for the analysis of most phenomena relevant for SMR, but they may require separate validation or addition of modules in the case of single-phase or two-phase heat transfer or pressure drops in complex geometries such as for example in microchannels.

Wherever crucial safety relevant phenomena (e.g., dry out of fuel rods) are investigated and in case passive safety systems are exploited (e.g., natural circulation in accident scenarios), experimental characterization/qualification may be in any case required.

Furthermore, the thermal-hydraulic behavior is recognized as one of the key topics in the design and safety analysis of AMR fast reactors. Thermal-hydraulic challenges can be divided in three main categories: core thermal-hydraulics, pool thermal-hydraulics, and system thermal-hydraulics. For each of these main categories, a division is made between normal reactor operation, off-normal conditions and severe accidents. Seven basic phenomena are at the basis of the challenges mentioned above and require investigation, these are: turbulent heat transfer, thermal fluctuations, mechanical fluctuations, mass transfer, bubble transport, particle transport, and solidification.

The safety demonstration of AMR fast reactors relies in large part on the numerical simulation of various transients of interest. To qualify these simulations, the numerical tools used must be checked for correctness (verification). Their capability to correctly predict the physics of each transient must be assessed against an exhaustive experimental database (validation). Also, the uncertainties associated with the outputs of the calculation must be quantified (uncertainty quantification).

Additionally, Flow-induced vibration (FIV) is a widespread problem in energy systems as vibrations rely on fluid movement for energy conversion. Vibrating structures may be damaged as fatigue or wear occur. Given the importance of reliable components in the nuclear industry, FIV has long been a major concern in the safety and operation of nuclear reactors. In particular, nuclear fuel rods, heat exchangers, steam generators, and canned motor reactor coolant pump have been known to suffer from FIV and related failures.

Advanced reactors, such as integral PWRs considered for SMR or pool-type LFR considered for AMR, often rely on innovative component designs to meet cost and safety targets. Component that are the subject of advanced designs are the heat exchangers/steam generators, some designs of which forego the usual shell-and-tube architecture in order to fit within the primary vessel, or canned motor reactor coolant pump to accommodate a compact configuration as much as possible.

However, advanced designs have far less data available or qualified heuristic methods to predict the flow-induced vibration effects.

R&D projects for the development of a high-fidelity, finite-element analysis/computational fluid dynamics (FEA/CFD) approach, and validation tests by experimental facilities to the simulation of FIV are therefore needed.

In-service inspection

It can be assumed that existing nuclear codes & standards for the in-service inspection (ISI) / non-destructive testing (NDT) of large LWRs, e.g., ASME Sec. XI, RSE-M, virtually completely apply to LW-SMRs. Also, the practical demonstration on the effectiveness of NDT systems for LW-SMRs would follow well established inspection qualification methodologies like the European network for inspection and qualification (ENIQ) [21] and Practical Demonstration Initiative (PDI). The compact design of the NSSS of integral PW-SMRs most probably requires the development of specific NDT equipment or technologies or the adaption of existing NDT equipment and technologies and their subsequent qualification. The latter would also apply to ISI personnel that performs ISI of such reactors and thus handles the specific NDT equipment and is involved in the analysis of NDT data. Alternatively, where the conventional ISI, is challenging, the use of structural health monitoring (SHM) systems could be considered. The effectiveness of such systems in detecting flaws in the NSSS needs to be demonstrated.

Nevertheless, where NSSS components for liquid metal cooled AMRs are concerned, the compatibility of existing techniques (developed and used in water, sodium or LBE at lower temperature) with a high-temperature liquid metal environment shall be still verified or overcame by new fit for purpose techniques.

Specific components and materials

Immersed or regular PWR CRDM

Many SMRs concepts propose Control Rod completely contained in the pressure vessel, with immersed control rod driving mechanisms.

Use of internal CRDM has several advantages: above all, no risk of control rod ejection due to high differential pressure; reduction of stress-corrosion cracking issues at interface between control rod nozzle and vessel head or bottom.

The main disadvantages are related to the possibility of a complete inspection and access for maintenance. A conventional design with drive mechanism outside the core may comply more naturally with ISI requirements; moreover, CRDM demonstrated quite reliable in LWRs.

R&D and design efforts may be focused on the following points:

- Design featuring inherent safety insertion (no external energy required)
- Possibility to reliably test control rod insertion
- Remote Inspection of insertion mechanism (for immersed CRDM)
- Reliability: not too many spurious insertions
- Results from application of similar mechanisms in other application (hydraulic or magnetic mechanisms not completely new and already used in other applications)
- Use of materials and design (e.g., leak tightness) compatible with harsh environment

Innovative concepts of control and safety rods, as well as related drive mechanisms also based on stored energy, buoyancy, mechanical latch or curie point magnets, are of interest in liquid metal AMR. Concepts for compact passive safety shutdown systems (e.g., based on neutron liquid poisons, absorbing material beads, out of core rotating means, intrinsic flowering induced by thermal expansion) have been proposed to be integrated in compact cores, but need extensive testing and qualification.

Specific pumps (canned motor pumps, other compact components)

Many SMRs concepts propose Canned Motor Pumps, based on existing experience in LWRs. Wet coil motors are proposed in a few concepts (e.g., CAP200).

Despite Canned Motor pumps have been widely used in PWR, some further investigation may be required about the following points:

- Remote Inspection and Maintenance for SMR design, where pumps are integral with vessel
- Pumps failure modes and impact on core cooling (a blocked pump should not hinder natural circulation cooling)
- Effect of reduced size on pump inertia and transients due to pump malfunction
- Materials compatibility with harsh conditions, especially for integral design concepts
- Pump size: due to the reduced power output of SMR, power absorbed by pump, its size and cost may be not negligible

Other compact components deserving further evaluations are pressurizers, given that concepts featuring integral design with vessel, with quite specific shapes and sized are proposed.

For all pressure vessel internals, in general, issues related to material degradation due to irradiation deserve investigation (Irradiation-Assisted Stress Corrosion Cracking IASCC, Irradiation Assisted Corrosion IAC, creep, etc.): due to the reduced core size and volume to surface ratio neutron irradiation effects can be more significant than in conventional LWRs.

Mechanical and magneto-hydro-dynamic pumps for liquid metals are being considered for AMR concepts of smaller size, but require dedicated developments and test for bearings and sealing solutions, as well as for compensation of mechanical instabilities on long shafts (potentially subject to buoyancy forces) and for the assessment of pumps behavior in accidental transients (e.g., characterization of coast down and pressure drops of free spinning or locked rotors, etc.).

Compact steam generators (alternative material to SS/Ni-based alloy 690, clogging deposits)

Compact steam generators operation and design can be based only partially on the existing solution for LWRs:

- Size is significantly smaller, not only to match the lower power output but also to better fulfil modularity requirements and fit integral design concept
- Different concepts (e.g. helical coil, plate HXs) are proposed to reduce size, while maintaining a high heat transfer surface.

Among issues to be further investigated:

- Possibility of remote inspection and maintenance for integral concepts. Tube/channel rupture effect should also be investigated;
- Effect of the reduced stored thermal on transient's evolution: large U-tube SGs in LWRs allows removing a significant amount of decay heat even when not fed by freshwater;
- The reduced overall thermal capacity may result in larger transient thermal stress than those experience in larger LWRs SGs;
- Tubes material: tube bundle in Ni-based alloy 690 showed limited sensitivity to stress corrosion cracking. Selection of alternative materials should minimize sensitivity to known phenomena (such as Stress corrosion cracking SCC or Intergranular stress corrosion cracking IGSCC) and identify other performance or structural integrity degradation mechanisms (deposit, clogging, etc.);
- SGs materials for integrated solution: SGs integrated within pressure vessel may be subject to neutron irradiation, if not far enough from the core. Irradiation Assisted Corrosion and Stress Corrosion Cracking (IAC/IASCC) may become an issue;
- Blowdown of HX secondary side (especially for vessel integral design);
- Steam quality/residual humidity as a function of turbine load (for concepts with load modulation);
- Parallel flow instability;
- Tube bundles restrain system suitable to avoid internals damage due to "whipping" effect (for integrated solutions).

Prototype construction – with industry support - is required for both validation of design codes and for identifying design solutions suitable to be realized to industrial scale and in a modular fashion.

Reactor structural materials and coolant chemistry control for LFR

Corrosion and Liquid Metal Embrittlement (when applicable) are the critical factors in selecting the structural materials for the reactor vessel and internals. Austenitic stainless steels and ferritic-martensitic stainless steels have been commonly considered as the structural materials for LFRs, with the former preferred by some designers as typical austenitic steels, such as SS316, have demonstrated not to be susceptible to LME.

Experiments have confirmed that corrosion of the austenitic and ferritic-martensitic stainless steels strongly depends on the operating temperature and the amount of dissolved oxygen in the lead coolant.

Self-healing alumina-forming steels, as well as alumina-coated steels and Functionally Graded Composites, are potential candidates for structural materials operating above 550°C, but additional testing is needed.

R&D needs for the reactor structural materials are as follows:

- Develop and/or demonstrate material(s) for construction/protection of the reactor coolant pump impeller, to ensure reliable operation consistent with the operating life selected for this component;
- Demonstrate reference structural materials and oxygen control strategies for corrosion control under the operational conditions of an engineering-scale demonstration LFR;
- Develop and/or demonstrate advanced structural materials, and associated oxygen control strategy, for operation in high-temperature lead (above 500-550°C, up to ~700°C) and under irradiation conditions representative of the neutron flux and cumulative damage expected for the specific components that the materials refer to;
- Develop required Design and Construction code cases for corrosion resistant materials and/or materials cladding/overlay protection design methods needed for reactor construction and licensing.

To support the R&D activities for reactor materials, testing and analysis capabilities are needed, to include creep tests; material corrosion and LME tests in a high-temperature lead environment; and irradiation tests of the reactor internals.

Diffusion Bonded Heat Exchangers

Diffusion bonded heat exchangers (DBHX) have been originally proposed in Liquid Metal Cooled Reactors, but can be used also in any SMR, no matter which is the coolant. The main advantages of DBHX are easiness of manufacturing and compactness. Compactness makes them suitable for SMRs, not only for primary loop but also for the balance of plant.

Topics to be further investigated to make DBHX suitable for SMRs are the following:

- Sensitivity to clogging and coolant impurity contents (due to the presence of micro-channels)
- Lack of established design, manufacturing and testing rules within existing construction codes (ASME, etc.)
- Possibility of In-service Inspection and Maintenance
- analysis of the types of failure of the component (credible break characterization)
- Evaluation of maximum temperature difference manageable

Prototype construction – with industry support - is required for both validation of design codes and for identifying design solutions suitable to be realized to industrial scale and in a modular fashion.

Advanced manufacturing

The term "advanced manufacturing" refers to a number of still relatively novel manufacturing methods for components. These are additive manufacturing (3D printing), powder metallurgy – hot isostatic pressing (HM-HIP), advanced cladding techniques (e.g. diode laser cladding) and advanced welding and joining techniques (e.g. electron beam welding). Advanced manufacturing technologies have progressed significantly in recent years and could be established in a number of industries (e.g. aerospace industry). Advanced manufacturing methods have significant advantages compared to conventional manufacturing methods. Additive manufacturing allows production of components with complex geometries much faster compared to conventionally manufacturing and is economically interesting where number of pieces is low, which makes it a technology for prototyping and for a selected set of components with a complex geometry, or to increase performance of components manufactured conventionally. Electron beam welding allows joining of metallic components virtually without the formation of heat-affected zones.

Because of their benefits, there are strong considerations of using advanced manufacturing methods to produce components of safety-classified SSCs and a number of corresponding R&D projects are currently underway. The use of advanced manufacturing methods to produce components of safety-classified SSCs essentially requires the coverage of these methods in nuclear design codes. Inclusion of advanced manufacturing methods in nuclear design codes requires a certain level of maturity of these methods and their technologies, which requires manufacturing process stability and reproducibility of process results of adequate quality that needs to be demonstrated in practice.

The currently ongoing Euratom Research-funded project NUCOBAM has the aim to produce a methodology to qualify additively manufactured components (via laser power bed fusion LPBF) to ensure that they meet requirements of nuclear design codes, essentially paving the way for LPBF to be included in nuclear design codes. R&D projects with the same aim are needed for all other advanced manufacturing methods.

Early involvement of a qualified supply chain for the development and testing of prototypical components will allow for optimized solutions for future deployment phases. Prototyping of scaled-down components allows for preliminary assessment and validation of design principles and performances, through dedicated testing and qualification in relevant environment. Collection of experimental data during testing operations following strict standards and procedures will provide feedback to designers and manufacturers for a continuous improvement. Moreover, data sets will also produce the necessary basis for improvement of design codes and will ensure the safety of innovative components, subject to the scrutiny of safety authorities and technical safety organizations throughout the licensing process.

3.2. R&D infrastructure

Currently different test facilities are used in Europe. Some facilities able perform thermal-hydraulic tests (reactor hydraulics, flow induced vibration, and specific NSSS components tests facilities) in Europe for light water reactors exist and have for instance been used lately for large PWR validation, such as for instance the Framatome Technical Center in Le Creusot, France (MAGALY, ROMEO, JULIETTE) similarly to the ones that are existing worldwide (e.g., in the United States, China, Korea).

For AMR, specific experimental facilities exist and have already tested some components relevant for SFRs (such as in the Institute of Physics of University of Latvia, KIT in Germany, and CEA in France), for LFRs (such as in ENEA in Italy, KIT and HZDR in Germany, SCK-CEN in Belgium, or currently under construction in Romania), for HTGRs to a lesser extent, and marginally for MSRs. Usually, such research centers also address the characterization of material behavior in their environment of interest (that is, sodium, lead or lead-bismuth eutectic, helium, …).

For material irradiation, accessible material testing reactors are scarce and would need to be further developed in the EU. Most of AMR vendors are considering using their reactor demonstrators or prototypes to demonstrate the material properties of NSSS components during the plant expected lifetime.

Those AMR demonstrators and prototypes are to be built as first steps, and would become part of the R&D infrastructure. These are not expected to include all the features of Generation IV systems, but are meant to be a step towards the commercial AMR, generally through different phases. Since the main limiting factors in terms of component lifetime are temperature, coolant erosion and corrosion, and irradiation, for which in most cases suitable materials have been selected but not thoroughly tested due to the lack of available infrastructures. The idea is to start with relatively modest temperature and also irradiation levels, to be increased in subsequent phases. In this way the research on materials can be split into several intermediate stages. The classes of materials that are expected to be used to design and construct advanced reactor demonstrators, prototypes, and then commercial reactors, including the different intermediate phases, have been analyzed in detail in EERA-JPNM (2019) [22].

Concerning advanced manufacturing, several facilities exist mainly in other industries than nuclear, but qualification of the material and of the manufacturing processes for nuclear applications generally still needs to be developed.

4. PASSIVE SYSTEMS

Passive systems [23] are widely used in Gen-III+ reactors. Passive systems (category D, i.e. typically based on active initiation) are a means for design simplification and cost competitiveness (e.g. no reliance on external power sources, minimization of components). A grace time is typically associated to system operation, meaning no human intervention or power source is needed to cope with system operation (simple actions like water makeup might be required after the grace time). SMR and AMR specific features (e.g., lower core power, integral design of the primary system, large core surface-to-volume and coolant inventory-to-power ratios, fuel design) strengthen the suitability of passive safety systems to reinforce the first three Defense in Depth (DiD) levels, toward higher safety level. All the consequent advantages concerning main safety functions (e.g. moderate decay heat amount helps to cover a mid or long-term period of grace, exclude large break loss of coolant accident LBLOCA initiating events due to a compact and integrated design, no use of pump and increase of thermal inertia using the passive system) should drive a significant reduction in the residual probabilities of core meltdown and radiological releases into the environment.

As demonstrated by several initiatives in different fora, multiple domestic and international collaborative activities are in progress or have been already done in relation to LW-SMR and AMR passive systems. As example, initiatives can be highlighted in H2020 Euratom Research and Training programme(e.g. ELSMOR [2], PASTELS [4], MCSAFER [24], PIACE project [25] currently on-going), in IAEA (e.g. International Collaborative Standard Problem on “Integral PWR Design Natural Circulation Flow Stability and Thermo-hydraulic Coupling of Primary System and Containment During Accidents”)[26], in OECD/NEA (e.g. “Status report on thermal-hydraulic passive systems design and safety assessment” that includes a benchmark on PERSEO experiments) [27], SNETP (e.g. the “strategic research and innovation agenda”)[28], and WENRA (report issued in 2018 on *Regulatory Aspects of Passive Systems which is presenting the Safety Assessment with Actuation of a passive system, Performance of safety function and Operating experience feedback*) [29] frameworks.

There are two interrelated needs on passive systems in general and for SMRs specifically. The safety assessment (including reliability of passive systems and deterministic safety analyses with passive safety systems) and qualification of calculation tools including meta-models (or surrogate models, that is approximation models that mimic the behavior of simulation model as closely as possible while being computationally cheaper to evaluate).

Deterministic analysis codes are the key elements used to develop safety analyses able to analytically characterize the phenomena/processes taking place in a selected NPP during a transient progression (e.g. design basis condition DBC, design extension conditions DEC) due to a postulated events. In order to apply these codes, the results of the transient progression have to be properly qualified, and the uncertainty of the results should be estimated. Four main specific needs have been identified considering the current State-of-Art: experimental assessment database, code modeling, system reliability, system designs and engineering process. Qualification highly relies on experimental support within the range of application.

In relation to the **experimental assessment database,** SMRs and AMRs, as advanced reactor designs, are in general characterized by some common features with the current generation of reactors and by other features typical of their design, e. g. low velocities and buoyancy. In relation to the common features with current reactors, it is necessary to identify which existing database can be used for the assessment of existing computational tools and characterize its representativeness. In relation to the features typical of advanced designs (containment process and interactions with the reactor coolant system; low pressure phenomena; phenomena related specifically to new system components or reactor configurations), it is necessary to review the current available experimental facilities, specifically developed for passive systems investigation, and to analyze the representativeness of the data. This process will allow to screen the facilities and their Thermal-Hydraulic (T-H) characterization objectives and investigate their ability to meet the specificities of the different types/requirements of SMR and AMR around the world. Once identified the experimental lack, will be investigated the possibility of building new European test facilities or adapting already existing ones for new specific test campaigns, strengthening the experimental capabilities of European stakeholders. In this process large Integral Test Facilities (ITF) and Separate Effect Test Facilities (SETF) should be considered, and the scaling issue should be addressed (e.g. use state-of art scaling methods (e.g. Hierarchical Two-Tiered Scaling H2TS) minimize the scaling distortions due to the scaling approach used, consider counterpart/similar test, full-height scaling and suitable flow areas are in general recommended for experimental characterization of passive systems wherein the important phenomena are the boiling- and condensation-processes, and buoyancy effect due to density change).

In relation to the **code modeling,** deterministic safety analyses codes need to be proven able to accurately predict the T-H phenomena typical of these advanced designs as integral configuration, and passive mitigation strategy based on natural driving forces. This coupled with the review of the model/constitutive equations implemented in the codes (or passive system models already developed but still not implemented in the codes) and their representativeness, allows to identify current modeling limitations. Major sources of uncertainty in code modelling need to be identified and characterized. Scaling issue should be addressed (e.g., validation of the codes with experimental data at different scales).

In relation to reliability, it is necessary to review the methodologies currently used (e.g., REliability of PAssive Systems REPAS and Reliability Methods for Passive Safety RMPS), support their use in the industries, and start detail studies to characterize the different transient scenarios (e.g., DBC, DEC). Also, it is necessary to have more investigation for assessing functional failure related to the T-H phenomena driving the operation of the systems and assess the related uncertainties, and possible interactions with active systems (if any). For this purpose, robustness against anything that may impair the good functioning or stability of the passive systems (wrecks, condensates, etc.) or that may provide uncertainty need to be investigated. Obstacles impairing adequate functioning shall be well identified and characterized. The reliability region of passive systems needs to be investigated and uncertainties should be considered. Additional line of defence shall be identified in case DiD line of the passive system fails. From the deterministic safety methodology, it is important to define requirements and appropriate methodologies to model the system behavior and its dependencies to the variation of accident conditions, without over-conservatism (including aggravating events).

From the design and engineering process perspective, it is necessary to reduce the width of uncertainty bands on the key parameters driving the physics of passive systems in DBC and DEC conditions, and characterize the entire spectrum of T-H conditions, that can take place along a transient, and that can affect the passive system target safety function fulfillment. With this regard, there is the need to focus on the instrumentation, which is important to make sure that passive systems operate as expected. It would also be beneficial to check how research reactors addressed and demonstrated the performance of their passive systems, when relevant. Validated codes have to be used and the model uncertainty has to be limited.

4.1. R&D gaps

In the development process of current and advanced reactors designs, the T-H analysis of single and two-phase fluid natural circulation in complex systems, under steady-state and transient conditions, is crucial for the understanding of the phenomena/process taking place along their operation.

In relation to the experimental assessment database, even if some large experiments in the world have been done for characterizing the T-H phenomena of passive system, only few experimental data have been currently used by the international community. Therefore, there is a lack of available experimental test campaigns on which we can rely for an exhaustive evaluation of the State-Of-Art T-H codes (some nuclear actors have built their own test facilities, but the results are not public). Also there is the need of large scale facilities characterized by low uncertainty measurement at low flow regime, and there is the needs of experiments characterized by well-instrumented tests for validating CFD in relation to 3D phenomena (e.g. mixing with buoyancy effects) and to produce high-resolution data still needed to advance the fundamental understanding of phenomena (e.g. flow boiling and two-phase flow, conjugate heat transfer, etc.) typically relevant for passive systems in advanced reactor concepts.

In relation to the codes modelling, State-of-Art tools have been evaluated against current operating reactor phenomena (e.g., high pressure, forced convective flow, etc.), and the validation of the deterministic safety analyses codes for all passive system operation mode will be necessary and relevant for several challenges to complete. Some activities have been done or are currently in progress in domestic and international collaborative framework to assess the capability of code for specific passive system phenomena. However, efforts still should be made to exhaustively validate state-of art codes with the specificities of passive systems (low pressure, natural circulation, condensation heat exchange, non-condensable gases, flow stratification, etc.). Currently there is still a need to develop specific models for new reactor configurations and components available in the SMR and AMR designs (integrated reactor pressure vessel RPV and flow distribution, compact steam generator SG, specific passive systems, etc.). Notably, AMR, although being based on different fluids as coolants, typically rely on water or air based safety systems for the decay heat removal function and could benefit from experimental data and methodologies developed for water based SMRs. Therefore, dedicated large scale facilities will be needed to evaluate the ability of the codes to accurately reproduce integral configurations and passive system loops (e.g. pressure drop at different mass flow rate, etc.), the strong coupling between the Reactor Coolant System RCS the containment, and 3D phenomena.

In relation to reliability, passive system functional failures have to be addressed by SMR designers and have to be considered also in an independent safety review process. Therefore, in relation with deterministic safety demonstration, guidance on requirements specific to passive systems and their features (activation, no external power, etc.) have still to be agreed together with guidance on the methodologies appropriate to model the system failure modes.

In relation **to design and engineering processes,** it is still necessary to characterize passive systems initial conditions, investigate if installed they meet the required performances in accident conditions, generalize using validated codes their use from DBC to DEC scenarios including extreme events, and how to manage their maintenance.

4.2. R&D infrastructures

Currently different test facilities are used in the world. In Europe examples are: INKA [30] (Framatome, Germany), THAI [31] (Becker technologies, Germany), PANDA [32] (PSI-Switzerland), PKL-SACO test facility [33](Framatome, Erlangen), PASI and MOTEL test facility [34] (LUT, Finland), PERSEO and HERO2 [35] (SIET, Italy), NACIE, CIRCE, HELENA [36] (ENEA, Italy). Outside from Europe examples are: OSU-MASLWR (OSU-USA, today called NIST), FESTA (KAERI- KOREA). Such facilities are relevant for water passive systems.

5. SEVERE ACCIDENTS

SMR should firstly be designed with advanced inherent safety features, through reinforcement of the 1, 2 and 3 Defence in Depth (DiD) levels, aiming at drastically reducing Severe Accidents (SA) likelihood (already by design) and strengthening mitigation measures to practically eliminate the need for offsite emergency response.

This implies efficient quantification of each individual mitigation feature as well as their combined performance, through sound and robust risk assessment approaches, to address timely regulatory requirements and allow completion of proper safety demonstration. This means that numerical tools involved in safety demonstrations should be extended, if needed, and validated with data representative of potential SA scenarios of each SMR designs. Hence, high-standards experimental programs, with specific attention to instrumentation, facility scale and design boundary condition, should be developed to support the highest accuracy feasible in the safety analysis, analytical tools, and the risk assessment methodology.

Given the expectation of a near-term deployment of SMRs in Europe, actions should be articulated to build suitable collaboration platforms to develop a consistent work plan to address these challenges and allow for a sound independent safety review process.

Given the wide variety of SMR, challenges raised are multiple. On one hand, common considerations can be identified for most SMR concepts (e.g., smaller containments and integral concepts, reduction of diversity and redundancy due to increased modularity, multiple units in the same site or structures, sharing of safety systems and Main Control Room MCR). On the other hand, specific considerations might probably need to be considered, as the SA phenomenology, the mitigation features and thereof R&D background, might be design specific. Especially, SMR concepts based on a “compaction” of well-known LWR, so-called LW-SMR, can benefit of the acquired knowledge and know-how on LWR to a much larger extent than AMR concepts.

Consequently, the R&D gaps are described separated between LW-SMR and AMR.

5.1. R&D gaps

LW-SMR concepts:

For LW-SMR, high-level research needs on SA are categorized under two inter-related sub-topics:

- **Sub-topic 1: Identification of potential or postulated SA scenarios**

  For LW-SMR, available knowledge on large LWR would support this need in a straightforward manner. Nonetheless, specific efforts are needed to select more precisely potential SA scenarios, notably due to the impact of integral designs, smaller containments, and increased role of passive systems (link with previous topic). To support this need, a combination of deterministic and probabilistic tools and methods would be relied upon along with engineering judgment.

  An emphasis is set at this stage on the need to develop further dedicated Probabilistic Safety Assessments PSA tools and methods as they could be less advanced or applicable than current deterministic tools and methods, notably given the need to have access to detailed designs as far as possible. In this respect, getting interactions with and data from SMR vendors need to be highlighted.

- **Sub-topic 2: Identification of specific research needs for the potential / postulated SA scenarios**

  Along with sub-topic 1, more specific “net” needs could be identified, starting from a “comprehensive list” of needs to which “credited” needs filled by existing knowledge and ongoing frames for large-LWR could be subtracted. The process to obtain this list of “net” specific needs would therefore follow a three step approach:

  - Step 1: **Experimental and analytical needs needs** (comprehensive list of needs);
    - With the driving purpose to ensure efficient and timely safety demonstration in line with regulatory requirements
  - Step 2: **Applicability and transfer of large-LWR knowledge** (credited needs);
  - Step 3: **Achieve a list of “net” needs for LW-SMR research on severe accidents**.

  The aim is on one side to identify feasibility studies for existing experimental facilities and programming potential for new devices to address particular thermal-hydraulics and SA problems. Besides, it aims at developing the modelling and specification of the measurement tools to allow finally relevant validations of numerical tools that would support the licensing process. Eventually, if needed following these validations, it would also support identification of requirements for the development of analytical tools.

  On the other side, it should however not preclude the use of existing tools and best estimate methodologies that could already prove to be beneficial and improve the estimate of the calculation uncertainties to characterize the fields for which a better knowledge is necessary.

  Existing tools and methodologies should certainly and primarily be applied in the following areas:

  - **Area 1: RPV integrity**

  This high-level R&D need can be mostly related to the sound demonstration on In-Vessel Retention by External Reactor Vessel Cooling (IVR-ERVC) mitigation measures, considering the latest state-of-the-art knowledge on large-LWR and its potential applicability to the concerned LW-SMR design. Indeed, even if SMR safety is based on IVR-ERVC strategy success due to weak residual power and that leads to substantial margin, the Euratom Research and Training Programme complementing IVMR program has shown that several other parameters, applicable to LW-SMR, are to address the success IVR-ERVC concept for safety demonstration.

Besides, the integral design and compaction of SMR might call upon for research needs (e.g. impact on RPV inner structures of an in-vessel steam explosion, other thermal effects of SA).

- **Area 2: Containment integrity**

This high-level R&D need focus on the impact that integral designs and compact containments can have on the SA progression and on the containment integrity. Phenomenological issues to be addressed would derive from the knowledge of large-LWR with respect to LW-SMR specific boundary conditions (e.g., accident tolerant fuels, hydrogen generation and distribution, use of passive autocatalytic recombiners, containment spray, containment inertization, filtered containment venting, steam explosion, fission products release and distribution behaviour).

- **Area 3: Dose calculations**

This R&D need is identified given the claim of some SMR vendors to limit the Emergency Planning Zone (EPZ) to the site boundary and as the concept of EPZ relates to the evaluation of radiological releases, and so to the SA released source terms. Although not related to SA phenomenology, it is deemed important to include it to derive pertinent Figures Of Merits (FOM) and insights to assess the acceptability of SMR designs. Eventually, assessing radiological doses for distances limited to the site boundary might be challenging with existing tools and methodologies not developed for close-range dispersion or consideration of buildings effects and which should therefore be subject to research as well.

The level of detail of such tools and methodologies along with the effort to develop them should however be commensurate with the expectations of the safety demonstration (link with WS2). Indeed, some simplifications and/or conservatisms could potentially be considered given that radiological source terms of SMR in SA conditions are expected to be relatively small.

AMR concepts:

For AMR, the same generic two high-level research needs on SA can be kept, i.e.:

- Identification of potential and/or postulated severe accident scenarios;
- Identification of specific research needs for the potential / postulated scenarios.
    - Here also with supporting areas on RPV integrity, containment integrity and EPZ.

Specific contents should be adapted given the wide variety of technologies (e.g. HTGR, SFR, LFR, MSR,).

Except for HTGR's first R&D needs hereunder, it is not detailed in this document given, their lower level of technical readiness and longer-term expectation for deployment.

HTGR SMR first research needs: Firstly, although releases from the fuel in normal and accident conditions are well known, there are still uncertainties in the determination of the source term released to the environment and for which new experimental data would be needed (e.g., core degradation behavior, crediting graphite adsorption, adsorption on internal structures and walls, effect of depressurization). Secondly, given that HTGR AMR aims mainly at providing heat to industrial processes, i.e. close to its usage, the R&D need concerning EPZ assessments and dedicated tool for LW-SMR (i.e., Area 3 of Sub-topic 2) is reinforced.[1]

[1] **Important note:** A prerequisite that should be addressed at a "Licensing" level (link with WS 2), is firstly the definition(s) of what a SA is for these concepts.
Indeed, the "conventional" definitions referring to core melting or degradation (e.g. IAEA, WENRA Reference Levels) become inadequate for some AMR concepts, especially those envisaging liquid or molten fuels.

Conclusion:

The LW-SMR severe accidents approach will capitalize on the large light water reactors SA approaches and R&D results. However, by looking at the current initiatives that are already finished or are on-going in different fora, it appears that the LW-SMR and AMR severe accident investigation is very limited and LW-SMR / AMR safety assessment, with best estimate methods, is only starting to be addressed within the HORIZON-Europe SASPAM-SA project. Therefore, the systematic analyses of the applicability and transfer of the current available severe accident experimental database (developed for current operating larger reactor) for SMR safety assessment studies (including notably the scalability question),, the analyses of current codes capabilities to simulate severe accident phenomena are novel topics of current high interest. Consequently, identification of experimental and code validation gaps should be carried out to subsequently define action plans to address these gaps.

The research activity developed along the R&D&I roadmap will be relevant for SMR technology. The research activity will contribute to the development of the phenomenological knowledge and of the deterministic and probabilistic safety analyses tools and methods needed for the improvement of the safety demonstration and the potential evolution of designs of SMR.

5.2. R&D infrastructures

Currently different test facilities exist in the world. In Europe examples are QUENCH [37] (FZK, Germany), ThAI [31] (Becker technologies, Germany), or PANDA [32] (PSI-Switzerland). The current challenges are for instance the mixing/combustion phenomena of the LW-SMR small containment, which have not been addressed by larger existing nuclear power plants.

6. MODULARIZATION

Two nuances of the “module” concept are typically considered: modularization (i.e., standardization of design, modular factory-fabrication, and on-site assembly of the plant to shorten the construction schedule) and modularity (i.e., capability to install multiple units on the same site potentially sharing auxiliary systems, thus increasing the flexibility of the plant and reducing capital costs).

Modularity allows for a better exploitation of nuclear sites and for a more competitive overall business case, thanks to the shared infrastructures, but poses undeniable safety and regulatory concerns that should be addressed on a case-by-case basis. The topic will be covered by WS2 devoted to safety and licensing of LW-SMR and AMRs.

On the other hand, modularization is an approach derived from naval construction and already successfully applied to Gen-III+ reactors. Factory fabrication and then onsite assembly of large modules is more and more used also for large plants and could be further optimized for smaller sized plants, thus leading to most of fabrication, assembly and testing activities carried out in factory (i.e., in a more controlled environment, not subject to weather conditions, and better monitorable from a quality assurance/control viewpoint). Modularization also requires a specialized supply chain, which will be investigated in WS4.

Four construction technologies are of specific interest:

- Modularization: Modular construction allows parallel construction activities to proceed with Significant reductions in construction schedule. Modular construction can include the system modules that are fabricated off site under controlled environment in a fabrication facility as well as the structural modules that are pre-fabricated and transported to the site for installation. In practice a module can consist of an assembly of multiple components such as structural elements, piping and

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As another example, the definition given by a group of TSOs in the frame of the H2020 project GEMINI+ dealing with HTGR is the following: *“a severe accident is a set of events and processes involving significant core degradation which has resulted or may result in significant release that could be of radiological safety significance”*.

valves, cable trays and conduits, instrument racks and electrical panels, access platforms and ladders or stairs, and other items.

- Slip Forming: Slip forming allows continuous construction of a structure. The concrete is poured continuously between two climbing wall faces and multiple platform levels allow for work to continue. By using this technique, construction time of a concrete reactor building is cut down significantly.
- Steel concrete (SC) structures: SC is the name of a generic steel-concrete composite construction system using planar components comprising two steel plates connected by a grid of tie bars with structural concrete between the plates. The plates act as load bearing formwork during the placement of the concrete (core) and, in the completed condition, they provide the reinforcement to the concrete. The tie bars, apart from holding the two plates together during transportation, erection and concreting, act as transverse shear reinforcement. Composite action between the steel plates and the concrete core is achieved through the use of headed shear studs welded to the steel plates.

This technique maximizes offsite prefabrication and minimizes onsite activity in order to reduce overall construction time.

- Open Top Construction: Open top construction facilitates installation of large components and large modules. In concert with the modular construction, it leads to significant reduction in the project schedule. In open top construction, the reactor building is partially completed and left open at the top and large components can be lowered into place from above with heavy lift cranes and then installed. Open top construction permits more activities to be progressed in parallel because the placement and installation of modules can occur through the open top of the structure with the use of heavy lift cranes.

The advantages of the advanced construction techniques can be summarized as follows:

- Reduction in project schedule by allowing parallel construction activities on system and structural modules
- Reduction in manpower needs at the project site
- Uniformity in systems and structural modules for multiple units at the same site and/or of the same design at different sites.
- Better quality control through initial testing of the components at the fabrication facility.
- Reduction in facility footprint
- Reduction in system components
- Reduction of work congestion at the construction site
- Mass production capability providing economies of scale
- Significant cost savings.

Modularization is a cross-cutting aspect fully applicable to LW-SMR and AMR concepts.

6.1. R&D gaps

Beside experiments and modelling aiming at qualifying new construction techniques, according to accepted codes and standards in the nuclear industry, most of the challenges of modularization are related to engineering, logistics, and project organization, rather to R&D activities.

Capability and capacity are required to fully cover the life cycle (i.e., design, manufacturing, operations, maintenance, disassembly, and disposal) of mechanical modules, which fit all electrical, mechanical, piping, control systems and structural elements and shall be commissioned and validated to the maximum extent before delivery on site.

Modularization success requires embracing a dedicated philosophy from initial concept design onwards. In particular, modularization imposes methodological changes from a system engineering standpoint: functional specifications at system level and system arrangements need to meet the requirements for factory fabrication, integral testing and transportation, thus including ab initio management of physical and functional interfaces. These interfaces depend on:

- Coupling, referring to the interdependence among multiple interfaced modules that are required to fulfil system functional requirements (a change to one module requires a change to the other)
- Cohesion, referring to the bounding of internal elements within the same module.

Increasing cohesion helps reducing coupling, thus minimizing overall complexity throughout the whole module, and plant, lifecycle (easier testing, maintenance, and disassembly).

The interface management in modularisation may increase design costs and even result in more rigid construction management at site (e.g., fixed erection sequences). Therefore, a strong and reliable methodology shall be developed.

Purely structural modules require proper combination of design codes (e.g. ACI-349 and AISC N690 in the US standard, EUROCODE in EU), specific connecting solutions (e.g. mechanical couplers) and qualification. Long-term reliability of structural modules may raise concerns in relation to the extended lifetime of SMR/AMRs.

A fully modularized approach to SMR/AMRs conception is expected to benefit from:

- System engineering methodology oriented to modularization, encompassing electrical, mechanical, piping, control systems and structural engineering disciplines towards an integrated layout oriented to maximise cohesion and to incorporate manufacturing/installation/commissioning aspects. Extension of Building Information Modelling (BIM) to incorporate nuclear specific and modularization aspects and processes will likely also assist the digitalization of the supply chain.
- Structural reliability analysis methodologies for composite structural modules, based on existing knowledge of probabilistic/reliability structural integrity methodologies and tools, correlating failure modes, material uncertainties, numerical codes limitations, correlations through probability distributions. Testing based on several trails combined with sensitivity analysis, as well as digital twin structural integrity monitoring, might be required.

A further aspect to be properly taken into consideration are the several layout constraints existing in the design of an NPP because of the functional and physical interactions between systems/structures (e.g., flooding, pipe whip, jet impingements, shielding, as low as reasonably achievable ALARA requirements, etc.) which makes more difficult to optimize modules as a "self-standing" construction problem (as in other industry applications) and require proper techniques to facilitate adjustments at various design stages.

Issue and Challenges:

Key issues for application of advanced construction techniques can be summarized as follows:

- Advanced Construction Techniques discussed above (modularization, SC structures, slip forming, and open top construction) require considerable advance planning and detailed engineering to support the fabrication and assembly of large modules for the structures and systems.
- Demonstration that the mechanical behavior of the SC structures members meets the safety objectives, over time and under all plant conditions.
- Capability to detect concrete placing defaults, and to demonstrate that the remaining defaults are acceptable.
- Modular construction involves bigger logistical challenges. This involves construction or fabrication at off-site facilities and transportation over long distances. Transportation by barge is the preferred route for large modules. The land route transportation restrictions may limit the design and the size of the construction modules.

- Some activities may involve first-of a-kind engineering activity.
- Modularization involves the use of heavy lift cranes.

The very heavy lift VHL cranes are a costly equipment to erect and operate at the site.

- Modularization and off-site fabrication may require setting up or expanding existing factories or manufacturing facilities to accommodate the module size and scope. This may involve additional expenses.
- Larger modules may need to be designed and fabricated as multiple sub-modules, which can then be assembled at the site.
- Open top construction methods will require the use of a temporary weather cover.
- Module connections to the structure must be precisely designed and the installation sequence determined in advance. Reliability of these joints and connections may require additional analytical methodologies and their validation.

Decisions to apply modularization, open top construction and other advanced technologies must be made early in the project, ideally at the conceptual design stage. The equipment modules should be designed to fit into their spaces in the appropriate structures or structural modules. The structural modules must be designed considering the lift capacity of the cranes to be used at the site and other logistics such as transportation to the site. From transportation perspective, barges can transport much larger and heavier modules than the truck transport. Larger modules can also be planned as multiple sub-modules that can then be shipped to the site and then assembled into the larger modules prior to installation.

Decommissioning is a unique part of the lifecycle of a nuclear power plant, and it requires a different set of activities to be planned and implemented. From the past lessons learned from decommissioning of existing reactors, recognition of the above was not always a fact. Also, from the past lessons, decommissioning was not given much consideration during the design phase of these reactors.

Modularization and advanced techniques applied during construction will facilitate intact removal of large components during the decommissioning phase. Precluding the necessity of segmentation of the pressure vessel and other large components has benefits in terms of reduction in worker radiation exposure, reduction in hazards for potential dispersion of contaminants, reduction in total waste produced, and more cost-effective waste disposal.

6.2. R&D infrastructures

The R&D gaps of the modularization are rather expected in the frame of the qualification according to a given set of codes and standards. The performance of the technique could be assessed in the frame of an actual large power reactor construction (such as the Hinkley Point C project in the UK for instance) or a future SMR construction.

Some R&D activities could nevertheless focus on demonstrating that the mechanical behavior of the structure is consistent with the simulation, and on the efficiency of quality control measures of the structures during or after the construction.

In Europe, the SCHEDULE project [38], which has been funded by a grant from the European Commission’s Research Fund for Coal and Steel, has completed the construction of a building, similar to some buildings of existing nuclear power plants, in France in 2022.

This building could then be tested and used to provide experimental data for the qualification of such type of innovative structures.

7. HUMAN FACTORS

This topic relates to Human Factors and Human Reliability Analysis issues related to multi-unit operation and passive safety systems.

In the wake of the Three Mile Island NPP (USA) accident, Human Factors (HF) and Human Reliability Analysis (HRA) are two related scientific disciplines highly involved during the design and the operation of NPP. Importance to take them into account as early as possible during the design process of new builds is acknowledged by international (IAEA [39], WANO[40]), European [41] (EUR, WENRA), and national entities (IRSN in France, UJV in Czech Republic, etc.). Today, HF and HRA are integrated in the licensing process in EU countries.

SMRs come with many specific features in their design compared to current NPP. Thus, many parts of their operation will be different. Assessing and evaluating the HF and HRA impact of these innovations is a mandatory step toward licensing of SMRs in Europe.

7.1. R&D gaps

Three specific features of SMRs will have major impacts on operations: multi-unit operation from a single control room, use of passive safety systems to mitigate accidents, and operation of multiple processes (nuclear process plus hydrogen or heat generation units) from the same control room. These specific features can also have impacts of HRA methods used during design and licensing process.

Multi-unit operations

LW-PWR in operation today are operated from a single unit control room. Nonetheless, some SMRs are intended to be operated from a multi-unit main control room (MCR). In some designs, operators and/or supervisors will manage several units which can be in different conditions (normal, abnormal, fault condition) and/or states (reactor in operation, shutdown, fuel loading, etc.) at the same time. This can have various consequences:

- Operators and/or supervisors over workload (management of multiple units as well as bad acoustics associated with co-activity) which in turn can impact monitoring and problem-solving activities, etc. In abnormal and accidental situations this could lead to impaired human performance and in turn, in safety issues.
- Confusion between units: operators and/or supervisors (or local operators) making actions/decisions on the wrong unit which could lead to safety issues.
- Confusion in the responsibility of operations of shared systems and facilities: an operator might think that another operator is monitoring a shared system and might not take an important action, which could lead to a safety issue.

Passive safety systems

Most PWR in operation today deal with fault conditions with active safety systems. Nonetheless, many SMRs designs intend to massively use passive (or semi-passive) safety systems (PSS). This will have many impacts on tasks and activities of control room staff especially during the management of fault conditions. Requirements for the design of crew organization (staffing, sharing of tasks), Human Machine Interfaces (HMI) & procedures, and training associated with PSS shall be defined.

Operating multiple processes (nuclear process + power generation + other added value process) from a single control room

In current NPP, control room and field operators are operating the nuclear and the power generation processes (as well as the sub processes like water demineralization associated with it). Nonetheless, some SMR vendors suggest that control room operators could operate these processes plus some added value processes like hydrogen or heating generation units. This raises questions regarding control room operators' workload, organization, and training as well as the design of the layout of the control room, HMIs and operating procedures and the associated requirements.

NOTE: if no European SMR vendors consider having the same operators from the same control room supervising the nuclear process, the power generation and another added value process (e.g., hydrogen or heat generation), this issue should not be investigated in the R&D&I roadmap.

HRA related issues

The methods of human reliability analysis have been developed and tested for the existing NPPs. Since the areas of concern, methods, results, challenges, etc. related to human reliability and human factors can be seen as relevant across many current up-to-date complex technologies working on non-negligible level of risk, these methods and approaches, are, to a significant extent, transferrable to the area of SMRs. Still, there are specific aspects of the human factors and human reliability related to SMRs, which may need to up-date the HRA methodology, or which may lead to selection of specific HRA method(-s) among the methods currently used worldwide. In addition, it may be useful to search for the specific features of SMR operation, which can lead to removing some areas typical for current NPPs HRA and limiting the necessary scope of HRA for the SMRs.

7.2. R&D infrastructures

Addressing the impact of SMR specific features on human performance, the design of SMRs and HRA methods shall be tackled in two ways.

The first way includes the use of a full scale multi-unit simulator where various multi-unit normal, abnormal & fault conditions can be tested. This simulator should ease the test of:

- Various HMIs,
- Various control room layouts
- Various types of operating procedures (including ergonomics aspects),
- Crew organizations (staffing and task allocation between control room agents),
- Acoustical features and devices (wall materials, unidirectional speakers, etc.).

To get valid results, the simulator shall be very close and specific to a particular SMR design. Moreover, using a process simulator implies that the operating crews shall be trained thoroughly before tests can be carried out.

In addition, to tackle the issue of the operation of multiple processes from the same control room, the full-scale simulator should include the process simulator (and associated HMIs and procedures) of the other added value process operated by the control room operators.

The results obtained in this simulator will be used to define requirements for the design of control rooms, procedures, HMIs, and crews' organization that do not impair human performance.

Considering HRA method, having a simulator will give access to the training of the operators. This may significantly help to make the HRA methods proposed more flexible to address the SMR specific features and the results of HRA for SMRs more realistic. Indeed, the operational procedures (particularly those used in abnormal and fault conditions) are key input for understanding the accident scenarios and the role of the operators in there. The availability of concrete procedures is then a key aspect of realistic HRA for SMRs.

HF tests with the full-scope simulator should be started in the very short term (at latest in 2024), to minimize the risk to delay the design of SMRs.

The second way to address the impact of SMRs' specific features involve no new infrastructure. Instead, it relies on:

- Sharing of experience with NPP or other complex industries that are operated from a multi-unit control room like Advanced Gas Reactors in UK and CANDU in Canada
- Sharing of experience with NPP or other complex industries that relies on passive safety system to deal with fault conditions like Westinghouse's AP-1000.

Results obtained from these shall then be extrapolated to the SMRs designs of interest to decide if these experiences are transferable.

8. USES BEYOND ELECTRICITY

Nuclear reactors produce heat, which is then used to produce electricity in a turbine generator. There are various uses for heat, and heat from a nuclear source has been used in various plants. Nuclear cogeneration has accumulated experience of 750 reactor-years worldwide. Mostly these are in the form of combined heat and power production, with a small fraction of heat generated used to provide district heating to communities close to NPPs. Other uses include steam supply for paper mill, cardboard factory, salt refining as well as seawater desalination.

Recent changes to the electricity market, especially the advent of variable renewable energies with priority feed-in have pushed nuclear power plants to also consider diversification to their energy service portfolios from sole electricity production. Thermal power of many reactor designs would enable a direct heat use of sizable fraction, if not all, of the total energy produced by the plant. Also, as heat is more difficult to transport than electricity, the siting close to the location of use is facilitated by the potentially more flexible siting of the plants. Several SMR vendors emphasize the range of energy services provided such as desalination, industrial heat, and district heating. Advanced reactors feature higher usable temperatures and increase the potential applications of nuclear heat.

Nuclear cogeneration and diversification of energy services is also an effective means for energy system integration of different energy sources to so-called hybrid energy systems, in particular those with large fractions of variable renewables.

In order to reach the carbon neutrality targets, the whole society needs to decarbonize. Currently in the EU, approximately one quarter of energy use is in the form of electricity, and despite a massive electrification a substantial part of industrial energy end uses will most likely remain non-electric for technical, economic and efficiency reasons. As a low carbon dispatchable energy dense source of heat, nuclear energy provides a unique solution to many needs at the required large scale.

Diversification of nuclear energy services would diversify use of nuclear energy through new applications beyond electricity thanks to nuclear deployment in the field of heat, hydrogen generation, power to X, and/or energy storage. The market potential for nuclear cogeneration for industrial uses is enormous, as shown by the WS1 study. With the increased hydrogen economy, the potential use of nuclear energy is increased even more.

LW-SMR/AMR systems at stake are the following:

- LW-SMR for heat-only applications (district heating/cooling or industry): specific design studies to deliver hot or chilled liquid water/steam
    - District heating/cooling
    - Industrial uses (limited in scope unless temperature boost methods are applied)
    - Hydrogen production methods
    - Some direct air capture applications
- LW-SMR/AMR in cogeneration mode
    - For process heat in industry (in particular steam as a commodity)
    - For hydrogen production when coupling to high temperature electrolysis or possibly to thermochemical cycles
    - For atmospheric CO2 capture
    - For power-to-X technologies to produce molecules like e-fuels and CH4 as feedstock
    - For desalination

8.1. R&D gaps

The R&D gaps vary a lot according to the different energy uses (CHP / district heating/ hydrogen production / industrial heat production, etc.) and the targeted applications.

In order to support the LW-SMR and AMR integration in a European decarbonized energy mix, the following R&D topics of interest are tentatively listed:

- Development of experimental platforms to qualify interactions between SMR and non-nuclear technologies, in order to increase global TRL

- Research on the potential issues in co-siting nuclear reactors with the heat users (industries, municipalities); safety requirements specific to co-location (e.g., nuclear combined with a hazardous chemical plant)
- Design and optimization of technical coupling technologies between nuclear plant and heat use facility;
- Development and validation of modelling tools aiming at providing digital twins
- Technological assessment and qualification of components, interfaces and whole systems between nuclear and non-nuclear subsystems (for energy use, energy conversion, energy storage, etc.) in real operating conditions (in particular power cycling);
- Assessment of the suitability of temperature boost technologies (electric, compression heat pump, chemical), or pre-heating with nuclear heat source
- Development and evaluation of short and long-term energy storage technologies (heat, cold, chemical, physical), considering:
    - the difference in scale and in requirements compared to renewable energy needs,
    - the suitability for nuclear application needs of innovations in non-nuclear fields;
- Country-specific interaction of nuclear regulations to regulations governing chemical industries (e.g. Seveso directive) when facilities are co-located.
- Market analysis for heat, cold, hydrogen and power to X (methane, ammonia, synfuel, etc.) which will yield to specific study cases answering local European energy scenarios
    - Hybrid SMRs designs and integration in such systems to answer to the specific study cases
- Analysis of the technical performances (operability, maneuverability, flexibility), and economical evaluations and safety analysis for the hybrid systems, providing input to other SNETP topics.
    - Assessment methodology, tools, etc.
- Development of specific LW-SMR/AMR designs aiming to be used in heat production / cogeneration role
- Public acceptance for such new nuclear energy applications
- Impact assessment (energy security, policy, industrial leadership, etc.)

8.2. R&D infrastructures

Infrastructures needed are mainly anticipated to be industrial demonstrators of the use of heat (district heating, or industrial heat coupled with an industrial process for a selected application).

9. WORKSTREAM 5 PERSPECTIVES AND TENTATIVE ROADMAP

SMR technologies have a great potential to play an instrumental role in the European ambitious environmental and energy sovereignty challenges. In the wake of the huge potential market opportunities associated with the decarbonization of our economies, many players outside and inside the European Union are active in bringing these technologies to reality in Europe. These SMR technologies include a very wide range of technology maturities, from LW-SMRs which embark incremental innovations in existing large light water reactors to breakthrough Generation IV concepts which are progressively improving the technology maturity level.

Meeting the net zero objectives by 2050 would mean that several timelines need to be considered depending on the readiness level of the technologies.

LW-SMR have the capacity to have first movers deployed in the 2030s, which would pave the way towards a deployment of series reactors of the same type in the following years.

AMR technologies are expected to be deployed in series later, because of the needed duration to meet the prerequisites for a first of a kind of the series: demonstration of the technology maturity for the reactor and its fuel, licensing readiness, and supply chain readiness.

It is important to keep in mind that the technological maturities among AMR technologies and thus the associated needed R&D effort are quite different from one to another, but that the overall timeline will be dependent on the speed at which all technological, financial, legal, social, geographical, and other prerequisites for deployment can be met. This statement is applicable to LW-SMR deployment speed as well.

However, for the sake of clarity of this first tentative roadmap, the R&D roadmap for AMR technologies outlines two possible steps, i.e., before and after the LW-SMR first movers are deployed. This tentative R&D&I roadmap aims at illustrating to which extent the R&D activities for both LW-SMR and AMR are common or specific, and how they should benefit from each other. These two streams of the roadmap represent complementary opportunities to reach and stay at the net zero objective in a sustainable manner.

It is also important to note that R&D activities would also be necessary for the already deployed technologies, with the aim of continuously improving the performance of these technologies, but it has been chosen at this stage not to show them in this roadmap.

The following sketches summarize the tentative conceptual high-level roadmaps for the 7 topics described above: The font color in the sketches outlines whether the R&D activities pertain to LW-SMR, to AMR, to both LW-SMR and AMR, or to fields connected but not directly related LW-SMR/AMR.

This version of the roadmap is very conceptual and would be revised and further detailed when specific LW-SMR designs and AMR technologies are confirmed and selected for deployment in the EU.

1. **<u>Core / Fuel tentative high-level roadmap</u>**

LW-SMR first movers	AMR first movers	

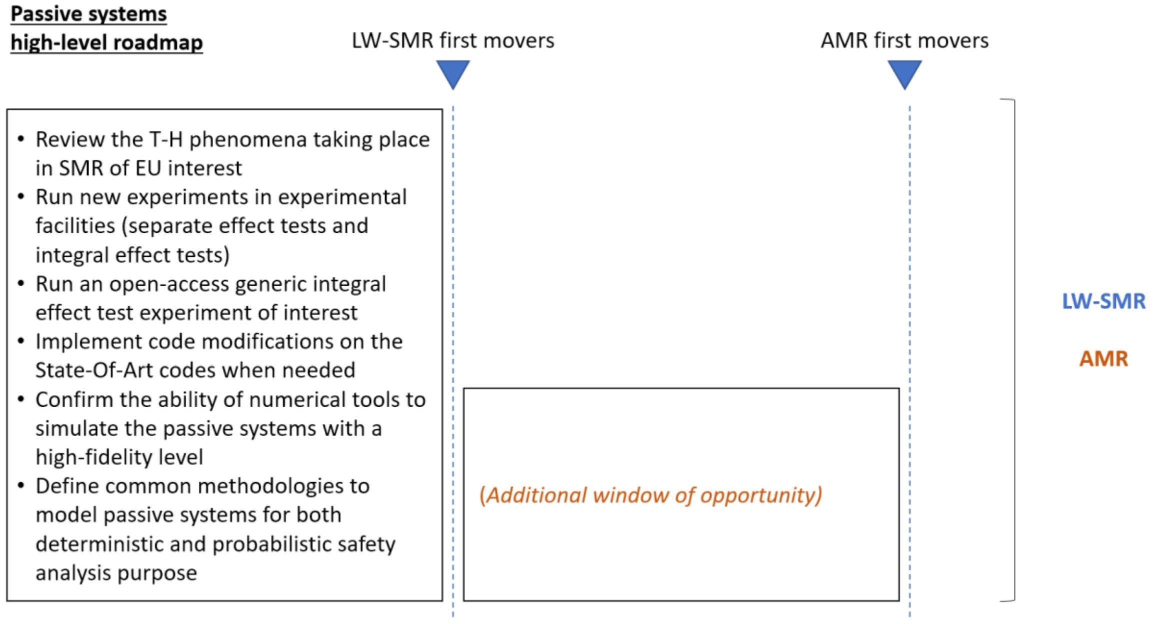
• Adapted fuel assembly qualification
  • Thermal-hydraulics (height/flow)
  • *Burnable poison in fuel rods*
• *Adapted in-Core instrumentation*
• *Core behavior / experiments for district heating LW-SMR*
		LW-SMR

• EATF development and qualification	• EATF deployment in LWR?	Large reactors innovations that will benefit to LW-SMR
• [HTGR] TRISO manufacturing and quality control development, fuel testing • [SFR/LFR] Prepare extension of fuel qualification domain, when relevant • [SFR/LFR] Plan HALEU fuel manufacturing • [LFR] fuel assemblies' behavior in lead environment • [MSR] data acquisition on fuel properties	• AMR fuel qualification in relevant environment, in "first stage" AMR demonstrators or in material testing reactor • AMR material irradiation and testing • AMR fuel cycle chemistry / processing • AMR fuel handling • AMR waste storage	**AMR**

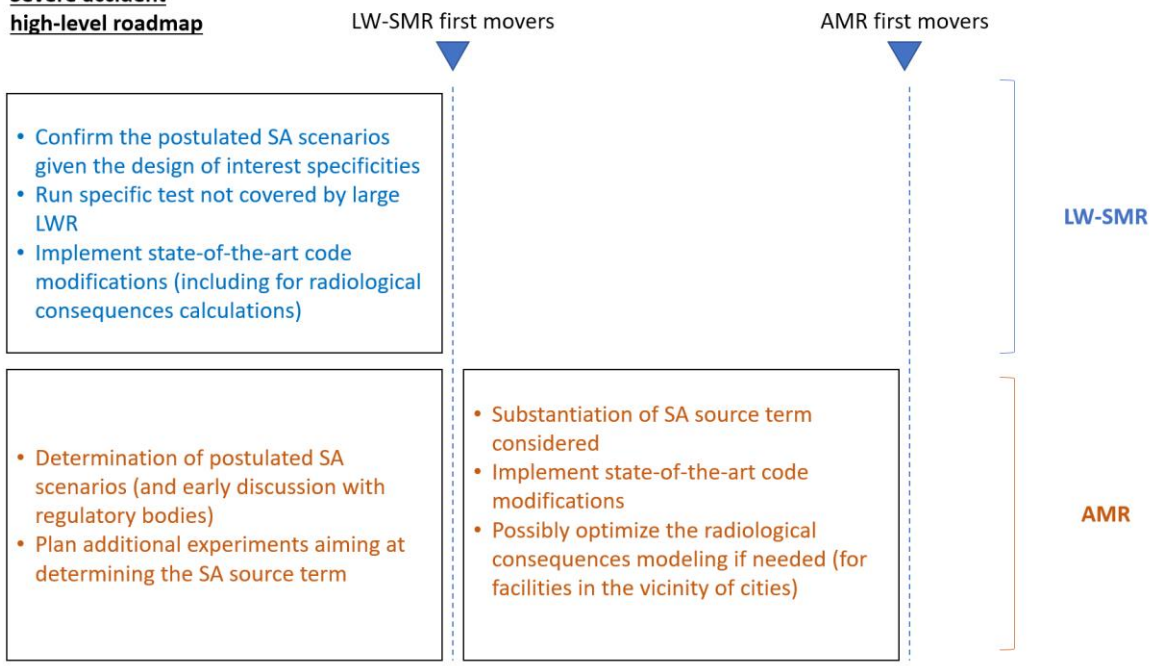
2. **<u>NSSS vessel and internals high-level roadmap</u>**

LW-SMR first movers	AMR first movers	
• NSSS components manufacturing tests • Codes and Standards gaps identification if any • NSSS components validation tests		**LW-SMR**
• Advanced manufacturing	• Advanced manufacturing qualification	Innovations that can benefit to all kind of reactors
• Structural material pre-normative research • Identify gaps for degradation in relevant environment (chemistry, irradiation), when relevant	• AMR structural material (incl. welding) ageing, irradiation, and testing • AMR structural materials modelling and characterization	**AMR**

3. **Passive systems high-level roadmap**



4. **Severe accident high-level roadmap**



5. **Modularization high-level roadmap**

LW-SMR first movers

AMR first movers

- Innovation in the way engineering, procurement, construction, and commissioning is performed, but not necessarily requiring R&D activities
- Demonstrating that the mechanical behavior of the structure is consistent with the simulation, and on the efficiency of quality control measures of the structures during or after the construction
- Development of methodologies for long-term reliability of structural modules

(Additional window of opportunity)

LW-SMR

AMR

6. **Human factors high-level roadmap**

LW-SMR first movers

AMR first movers

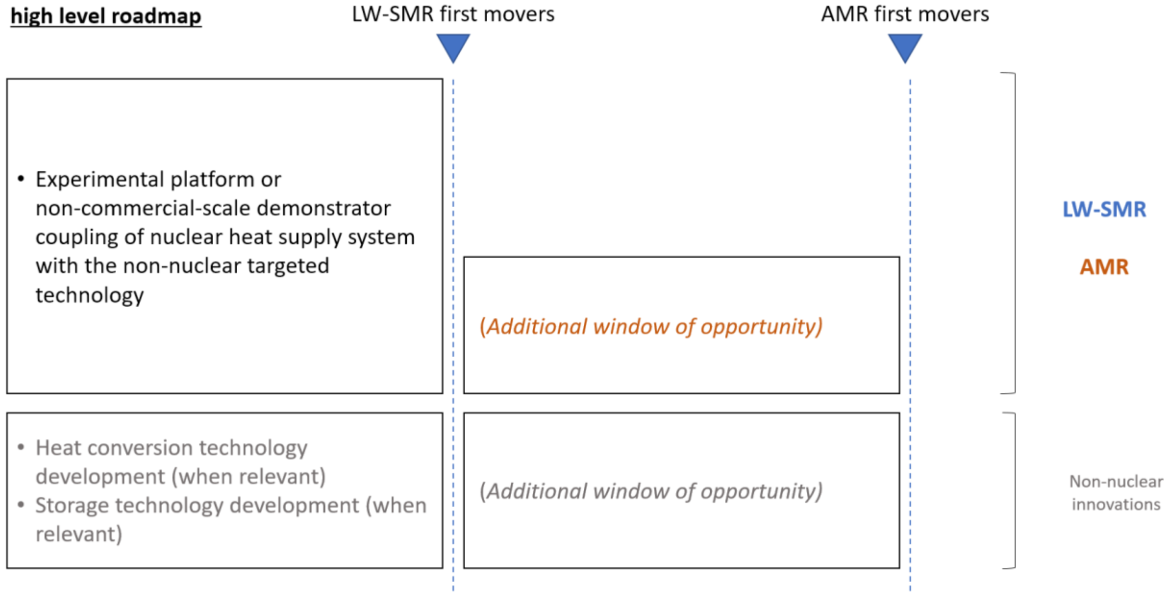
- Run a full scale (multi-unit if relevant) simulator where various (multi-unit) normal, abnormal & fault conditions can be tested: HMIs, procedures, crew organization, control room layouts concepts, considering the design specificities (such as multi-unit operation from a control room, passive systems, multiple process operation)

(Additional window of opportunity)

LW-SMR

AMR

7. Uses beyond electricity high level roadmap



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