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Status report on safety analysis in Europe from the operational flexibility andcogeneration viewpoi

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Summary

Status report on safety analysis in Europe from the operational flexibility and cogeneration viewpoint. The aim is to dentify and assess the potentially impacted safety margins of the SMR when integrated in a hybrid energy system, with overall coordination by IRSN. For this purpose, all the participants (in particular operators and TSOs) will analyse the constraints which would result from SMR adaptation to energy demand and response to transients and abnormal operation of the connected systems (e.g. thermal load and fatigue, core power redistribution, reactivity control, pellet?cladding interaction, etc.). The approach will be based on a survey of the best practices developed by the partners in the field of safety assessment of energy production flexibility and cogeneration (technical constraints, specific safety concerns, etc.). The study will cover feedback from Germany (GRS), France (IRSN) and eastern Europe (ENERGORISK). Then a methodology for assessment of relevant physical parameters and safety margins of the SMR will be established.

Approval

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D4.1 - Status report on safety analysis in Europe from the operational flexibility and cogeneration viewpoint

WP4 - Task 4.1

February 2023

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Abbreviations and Acronyms

Acronym	Description
AOO	Anticipated Operational Occurrences
ARCHER	Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D
AWE	Alkaline Water Electrolysis
BDBA	Beyond Design Basis Accident
BLEVE	Boiling Liquid Expanding Vapour Explosion
BOL	Beginning Of Life
CCGT	Combined Cycle Gas Turbine
CFR	Code of Federal Regulations
CIRTEN	Consorzio Interuniversitario per la Ricerca TEcnologica Nucleare
CMF	Core Melt Frequency
DBA	Design Basis Accident
DiD	Defence in Depth
DoW	Description of Work
EIA	Environmental Impact Assessment
ELPO	Extended Low Power Operation
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
EOL	End Of Life
EPRI	Electric Power Research Institute
EUR	European Utility Requirements
EU	European Union
EUROPAIRS	End User Requirement fOr Process heat Applications with Innovative Reactors for Sustainable energy supply
FOAK	First Of A Kind
FP7	Framework Programme No 7
FR	Fast Reactor

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GCR	Gas Cooled Reactor
GEMINI+	Research and Development in support of the GEMINI Initiative
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH
HTGR	High Temperature Gas Reactor
HTR	High Temperature Reactor
HTSE	High Temperature Steam Electrolysis
IHX	Intermediate Heat Exchanger
INSAG	International Nuclear Safety Advisory Group
LOOP	Loss Of Off-site Power
LWR	Light Water Reactor
LW-SMR	Light Water SMR
IAEA	International Atomic Energy Agency
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
LR	Large Reactor
LERF	Large Early Release Frequency
MSR	Molten Salt Reactor
NC2I	European Nuclear Cogeneration Industrial Initiative
NC2I-R	Nuclear Cogeneration Industrial Initiative - Research and Development Coordination
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
ORNL	Oak Ridge National Laboratory
PCI	Pellet Cladding Interaction
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RES	Renewable Energy Source
RTP	Rated Thermal Power
SBO	Station Black-Out
SCC	Stress Corrosion Cracking
SI	Sulfur Iodine thermochemical processes

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SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SPZ	Sanitary Protection Zone
SSC	Systems Structures Components
TANDEM	Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix
TES	Thermal Energy Storage
TSO	Technical Supporting Organisation
UNIPI	Università di Pisa
VCE	Vapour Cloud Explosion
VHTR	Very High Temperature Reactor
WENRA	Western European Nuclear Regulators Association
WPn	Work Package No n

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Executive Summary

In the present report the status of European studies on safety analysis of small modular reactors (SMRs) from the operational flexibility and cogeneration viewpoint has been considered.

The amount of work done in Europe and abroad in relation to the safety aspects of the inclusion of light water small modular reactors (LW-SMRs) into hybrid energy systems in a cogeneration pattern was found to be limited. This requested to draw information from the broader field of the studies on nuclear cogeneration applications for different types of reactors, where experience has been accumulated by specific projects. Nuclear plants are by the way presently adopted as heat sources for desalination, district heating and process heat, also in Europe, suggesting the possibility and the need to tackle the related issues by a systematic study.

Considerable work has been made in the frame of the European Nuclear Cogeneration Industrial Initiative platform (NC2I) for (very) high temperature reactors ((V)HTR); showing interesting analogies with the work to be performed in TANDEM; having already tackled relevant issues, the related projects provide very useful information to start a similar work on light water SMRs.

In particular, the reports of EUROPAIRS, NC2I-R and GEMINI+ projects constitute an interesting background for the work in TANDEM. Among the different principles emerging from these studies, the requirement that the safety of the nuclear installation will not be adversely affected by the coupling with cogeneration in hybrid systems represents a strong pillar in the adopted safety philosophy. The path followed in the EUROPAIRS project is particularly relevant also in relation to its deliverable D2.1 (Safety and licensing evaluation of a (V)HTR coupled to industrial processes, Baudrand and Noël, 2011), sketching a route to be usefully followed also in TANDEM for performing the intended job of setting up a methodology for the assessment of safety margins impacted by cogeneration.

Reports by WENRA, IAEA and the SMR Regulators' Forum provided valuable information about safety objectives and issues to be considered for setting up a meaningful methodology for safety margin impact assessment. Other documents have been also considered, coming from free literature and international and European organisations.

The considered works highlight requirements of flexibility of SMR power production both because of the needs of the cogeneration process and for the connection to a future electricity grid possibly dominated by intermittent renewables with a limited amount of storage. In such a situation, additional anticipated operational occurrences (AOOs) and/or load following procedures need to be considered, though load following is suggested to be neither economic nor completely in favour of safety. As a consequence, some proposals for cogenerating systems

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come up with the nuclear reactor operating mostly at full power, where flexibility is obtained by the repartition of the thermal output between the electrical and the non-electrical users, including reliance on storage systems.

The TSOs involved in the present action also provided their feedback on the following aspects:

- the assessment in France of safety aspects of non-baseload operating related to core/fuel and their flexibility ranges;
- the flexibility of normal reactor operation and the safety, security and safeguard issues relating to the inclusion of SMRs in a cogenerating environment.

Preliminary suggestions about a methodology for the assessment of the safety margins impacted by cogeneration are proposed at the end of the report. This methodology will be developed in the forthcoming deliverable D4.2; in D4.5 more sound conclusions will be finally drawn, basing on the analysis of test cases involving operational transient and design basis accident analyses, to be detailed in D4.3 and D4.4.

Keywords

SMRs, Hybrid energy Systems, Safety Analysis, Flexibility, Cogeneration, Europe

1 Introduction

Small Modular Reactors (SMRs) are presently considered as a promising technology for deployment of nuclear energy in Europe and worldwide in the short term and in the next decades. A recent review by the International Atomic Energy Agency (IAEA, 2020) indicates a growing interest by Member States about advances in SMR designs of different types, including light water reactors (LWRs), fast reactors (FRs) and high temperature reactors (HTRs), involving also their applications for non-electric purposes.

In line with the interest for non-electric applications, though considering also electric ones, the EU TANDEM Project (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix) in its Project Summary (TANDEM Grant Agreement, 2022) draws the attention to nuclear SMR systems hybridized *"with other energy sources, storage systems and energy conversion applications to provide electricity, heat and hydrogen."* The purpose of this hybridization is suggested in the fact that *"SMR technology thus has the potential to strongly contribute to the energy decarbonisation in order to achieve climate-neutrality in Europe by 2050."* In this aim, the project *"(…) proposes to specifically address the safety issues of SMRs related to their integration into hybrid energy systems, involving specific interactions between SMRs and the rest of the hybrid systems; new initiating events will have to be considered in the safety approach."* (ibid.)

The purpose to analyse the safety aspects of SMRs when included into cogeneration networks is the specific subject addressed by the WP4 of the project, under the lead of the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN), which is devoted to the *"Safety analysis of SMRs integrated into the hybrid systems"*. The issues addressed by this WP concern the potential safety impacts of intensive and flexible SMRs operation in a power system with significant intermittent renewable energy sources (RES) penetration and to analyse the safety aspects of SMRs when included into cogeneration networks. In this frame, the specific *constraints and risks* induced by the combination of a nuclear system with a cogenerating network need to be discussed and evaluated, considering the specific features of light water SMRs under development in Europe. In particular, *"A methodology for assessing the potential resulting impacts on safety will be proposed and be applied to safety case studies."* (ibid.) An obvious link with the WP1 of the project, devoted to the characterization of the hybrid systems to be considered, needs to be borne in mind to perform analyses pertinent for the addressed energy mix and cogeneration scenarios.

The specific outputs of WP4 have a specific interest for the discussion to be presented in this report and are explicitly mentioned hereafter:

- *"List of safety relevant parameters potentially impacted by SMR specific operational constraints,*
- *A method for demonstrating that SMRs can be safely operated within a hybrid energy system,*
- *Exemplification of this method by selected safety cases,*
- *A set of validated numerical models relevant for safety assessment of the SMR as part of a hybrid energy system."* (ibid.)

In this context, the purpose of this deliverable D4.1 is to present the status of the "*safety analyses in Europe from the operational flexibility and cogeneration viewpoint*". In particular:

> *"The aim is to identify and assess the potentially impacted safety margins of the SMR when integrated in a hybrid energy system, with overall coordination by IRSN. For this purpose, all the participants (in particular operators and TSOs) will analyse the constraints which would result from SMR adaptation to energy demand and response to transients and abnormal operation of the connected systems (e.g., thermal load and fatigue, core power redistribution, reactivity control, pellet–cladding interaction, etc.). The approach will be based on a survey of the best practices developed by the partners in the field of safety assessment of energy production flexibility and cogeneration (technical constraints, specific safety concerns, etc.). The study will cover feedback from Germany (GRS), France (IRSN) and eastern Europe (ENERGORISK). Then a methodology for assessment of relevant physical parameters and safety margins of the SMR will be established."* (ibid.)

In relation to the methodology mentioned at the end of the previous paragraph, it will be clear in the following that at only first proposals can be made in regard in this report. Results and information coming from neighbouring sectors of research are indeed not immediately applicable to our case of light water SMRs (LW-SMRs). The definition of the methodology will be addressed in deliverable D4.2 (Identification of potentially impacted safety margins and methodology for safety analysis of a SMR integrated in a hybrid system).

Through the first technical exchanges initiated with the other contributing TANDEM partners by CIRTEN – Università di Pisa (UNIPI in the following), in charge of coordinating the work for drafting this deliverable, it was immediately perceived that previous work on the specific subject of the safety aspects of LW-SMR combination with cogeneration is scarce in Europe and even worldwide; though a rather conspicuous literature does exist on light water nuclear reactor combination with industrial processes, mention to safety aspects is generally occasional, configuring this issue as a new territory to be explored in the frame of the TANDEM Project.

While this provides a greater relevance to the work to be done in this project, probably as a first-of-a-kind (FOAK) study in Europe, drafting this report requested to consider information coming from different sources, not always well targeted for the purpose.

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However, IAEA (2017) and IAEA (2017a) provide summary information mainly on large reactor in cogeneration applications, also considering existing applications of nuclear reactors in support to non-electric applications, highlighting interesting safety concerns. A great help was also found in the work done in past decades in the European Nuclear Cogeneration Industrial Initiative (NC2I) (see the NC2I Website), as a pillar of the Sustainable Nuclear Energy Technology Platform (SNETP) (see the SNETP Website). In this frame, projects specifically concerning High Temperature Reactors (HTR, or Very High Temperature Reactors, VHTR) dealt with safety issues related to the combination of those nuclear reactors with various cogeneration scenarios, providing also suggestions useful for our case, though they will need to be conveniently customised for LWRs and SMRs in particular.

General publications by various international organisations were also considered, sometimes finding useful suggestions, though they mostly needed to be transposed to the present context. Summary information on the status of the work performed in past years on subjects related to the purpose of this report in this specific field by the TSOs (IRSN, GRS and ENERGORISK) is also presented herein. The style used for conducting the survey in this report is the one of a reading guide of the addressed documents, with several verbatim quotations, in order to refer to the truly message reported in them.

As above mentioned, owing to the limited availability of previous work specifically developed on cogeneration by LWR nuclear hybrid systems, the methodology for the assessment of relevant physical parameters and safety margins in these systems is presently suggested in a sketchy way, deferring to deliverable D4.2 a better deepening and exploitation of the related concepts.

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2 Survey of some previous studies related to the safety of nuclear reactors with cogeneration in Europe and abroad

The documentation discussed in this Chapter is related to various aspects of nuclear reactors when interfaced with industrial plants in a cogeneration environment. As it will be noted and as it was anticipated in the Introduction, some of the considered documents are referring to conditions not directly applicable to the present case for one or more aspects; however, they are mentioned because they somehow contribute to form a general picture on whose basis the methodology for the assessment of relevant parameters and safety margins can be developed.

Among the sources of information that most contribute to lay the ground for the developments to be undertaken in TANDEM, the following projects developed in the frame of the NC2I platform must be mentioned. They will be addressed specifically in the first subsection of this Chapter; the general objectives of these projects are summarised hereafter.

- **The EUROPAIRS FP7 Project** (End User Requirement fOr Process heat Applications with Innovative Reactors for Sustainable energy supply) - Start Date: 1 September 2009; End date: 31 May 2011

"The objective of the EU-funded Project was to prepare conditions for the development of a European industrial demonstrator of the coupling of a (V)HTR in a power cogeneration (heat and electricity) mode with process heat applications. Such new application of nuclear energy would allow saving large quantities of fossil fuel resources and reduce greenhouse gas emissions of industry." (from EUROPAIRS Cordis Website)

- **The NC2I-R FP7 Project** (Nuclear Cogeneration Industrial Initiative - Research and Development Coordination) - Start Date: 1 October 2013; End date: 30 September 2015

"[…] The EU-funded project NC2I-R (Nuclear cogeneration industrial initiative - Research and development coordination) was established to support NC2I activities by preparing the conditions for developing a European cogeneration industrial demonstrator for next-generation nuclear reactors. The aim of NC2I-R was to commission a nuclear cogeneration prototype for testing and deploying this low-carbon energy technology in several energy-intensive industries. Project partners investigated several legal and safety issues for developing nuclear cogeneration and licensing technology. They focused on drawing up strict specifications for the demonstrator to ensure its viability and replicable production, and satisfy market demand. [...]" (from NC2I-R Project Cordis Website)

- **The GEMINI+ H2020 Project** (Research and Development in support of the GEMINI Initiative) - Start Date: 1 September 2017; End date: 28 February 2021

"[…] The overall objective of GEMINI+ project was to provide a conceptual design of a high temperature nuclear cogeneration system with ability to supply process steam to industry. Equally important objectives are providing a licensing framework for this system and a business plan for a full scale demonstration. An important task was to analyse innovative options which are of benefit for the demonstration of safety and performance, and which enhance the competitiveness and market potential of a nuclear cogeneration plant. Residual technology gaps have to be identified to point out necessary R&D actions. Selected applications had to be analysed including economic competitiveness. [...]" (from GEMINI+ Project Cordis Website)

The material developed in these projects and made available at different websites will be commented in the next subsection. They turned out to be very useful for starting our elaborations in TANDEM about the safety issues of LW-SMRs when included in cogeneration hybrid systems.

Two additional projects in the same line of research could also be addressed. One of them is The ARCHER FP7 Project (Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D) - Start Date: 1 February 2011; End date: 31 January 2015. However, a brief overview of its characteristics did not provide evidence that additional aspects with respect to the ones already addressed in the previously mentioned projects could be pointed out by the analysis of the work performed in ARCHER. Just for the sake of completeness, hereafter is reported what is mentioned about safety in the final Report Summary of the project:

"Safety

With respect to safety a comparison based on actual facts is hard to achieve as statistics are lacking for nuclear, let alone for an HTR. If the HTR system will be able to fulfil its promising safety characteristics, the HTR system might be a little safer than a CCGT which as such is relatively safe when compared with many other forms of energy generation. A rather different aspect of safety is the licensing process. For HTR, the licensing of a plant in combination with cogeneration has never been shown. Furthermore, much of the licensing expertise and knowledge from the HTRs which have been operated has been lost and needs to be retrieved and updated in line with current licensing practices." (from ARCHER Project Cordis Website)

The second project to be considered is the GEMINI 4.0 Horizon Europe project. *"Launched in June 2022, GEMINI 4.0 aims to build a low-carbon future for industry based on the experience gained through the operation of HTR and knowledge of hydrogen production processes acquired in the*

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previous H2020 project GEMINI+." (from the Gemini Initiative website). About its objectives, the following statements suggest a research path quite parallel to the one of TANDEM in relation to the use of nuclear systems in cogeneration that suggests, whenever possible, to consider useful interactions that could be quite profitable for TANDEM, given the longer term expertise gained by the GEMINI initiative in this field with respect to work related to LWRs.

"Many industrial processes require heat, large amounts of hydrogen and other energy products. The GEMINI+ project demonstrated that High Temperature Reactor systems can provide a competitive and safe solution for the CO_2 free cogeneration of the process heat and electricity needed by industry. The GEMINI 4.0 project aims to demonstrate that the GEMINI+ system can, in addition to CO_2 free process heat, provide a global solution for the competitive and safe decarbonisation of industrial activities, and confirm that this new form of poly-generation of various energy products does not negatively affect the safety of the combined plant.

The GEMINI 4.0 project will build on the groundwork laid by GEMINI+ and earlier projects carried out by NC2I, which defined the bases for the design and licensing framework of a HTR addressing European industry needs of process heat reliant on steam distribution networks that are already operated presently on many European industrial sites." (from the Gemini Initiative website)

The specific reports of the above projects considered in this survey will be mentioned below. Additional material considered was in the form of presentations provided by project and NC2I participants, papers and reports from available literature and freely accessible via internet.

It must be explicitly mentioned that in summarising this material in the following subsections there is no pretence to be exhaustive or 100% accurate in interpreting the message conveyed by the authors; the full reading of these reports is recommended for the further elaboration of the addressed concepts in the frame of TANDEM.

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2.1 Selected information from European Projects

2.1.1 Information from the EUROPAIRS Project

A very interesting source of information is found in the Deliverable 2.1 of the project entitled **"Safety and licensing evaluation of a (V)HTR coupled to industrial processes"** (Baudrand and Noël, 2011). ([1])

The report presents a quite comprehensive analysis of the safety and licensing aspects of a High Temperature Gas Reactor in cogeneration arrangements combined for producing: 1) electricity and steam; 2) electricity and hydrogen by High Temperature Electrolysis (HTE). The considered impacts are those of both the industrial plant on the NPP and, viceversa, of the NPP on the industrial plant and its productivity.

Two basic objectives were agreed by the working group which prepared material for the document:

"*1) The coupled facility (plant which is dedicated to the production of industrial products) shall not fall under nuclear regulation.*

2) The global safety of the nuclear plant shall not be lowered by the coupling" [i.e., coupling with the cogeneration process]. (Baudrand and Noël, 2011)

It is mentioned that *"The first point comes from industrial and nuclear operators. Actually, the nuclear plant shall be seen as a utility from the industrial site and no specific procedures or regulations related to nuclear safety shall be applied to the industrial processes."* (ibid.)

The first objective involves:

- ***"****the practical separation between the nuclear and the industrial sites, each one being under the responsibility of its own operator;*
- *the demonstration of the sufficiently low level of radioactive contamination of the coupling fluid that comes out of the nuclear site;*
- *the status of the workers of the industrial facilities is the same as the public, in terms of radiological protection and exposure limits."* (ibid.)

([1]) It must be noted that the report is categorised as "Confidential", though it is freely available online. An interaction with the Authors clarified that it can be used with no specific restriction in the purposes of the present TANDEM project (https://api.lgi-consulting.org/library/download-0beb34df7e9615cd43b9090989ca4848-2)

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An attempt to consider the two facilities, nuclear and industrial, as completely separated to avoid negative interferences is clear. The issue of the coupling fluids is repeated several times in the literature, addressing the possible contamination of the interfacing fluids by radioactive materials and, in particular, by tritium.

Moreover, it is stated that: *"Requirement n°2 derives from the fact that the vicinity of the two systems gives rise to specific hazards (toxic release, explosion hazards, etc.). Practically, there would be two specific safety demonstrations addressing each facility of the coupled system. But, the safety assessment of each facility needs to integrate the reciprocal impact of incidental and accidental operation of the plants. As an example, the nuclear plant safety demonstration shall integrate the potential hazards induced by the coupled process as external events."* (ibid.)

Therefore, here it is recognised that interactions of the two parts of the hybrid system are unavoidable, but the design should be made in order to assure that the safety of the nuclear plant is not decreased by the presence of the industrial installation.

It is then suggested that the presence of several sites in Europe already hosting LWRs in industrial areas may provide information on the way in which the hazards coming from either plant have been already considered in safety analyses. A particular concern is related to the presence of the control room of the industrial process within the evacuation area of the nuclear plant. There is the need to assess how the industrial plant can be shut down in case of danger. However:

"For the HTR concept, the evacuation area could be cancelled and the maximum protective measures limited to temporary sheltering in a limited area around the nuclear site. Such an approach, if demonstration is validated by the Safety Authorities, could be convenient for the coupled system because it would remove a constraint on the safety distance between the nuclear plant and the process." (ibid.)

Very evidently the above paragraph suggests an assumed peculiarity of the HTR plant that may or may not have a counterpart for a light water SMR (LW-SMR), depending on its design and the consequent estimated probability of occurrence of large early releases. This can be an area requiring an in-depth analysis in the frame of the TANDEM project as it may condition the very concept of safety distance (or exclusion area and similar concepts).

Security aspects are also addressed. In particular, it is argued that the access of the process (industrial) system workers should be conditioned to security clearance in the case in which the nuclear and non-nuclear process sites are close.

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After considering the general objectives as summarised above, the licensing aspects are then addressed. In particular, the following issues are considered.

- The question if the LWRs licensing process is adequate for the extension to the present case (HTR + cogeneration) is tackled; consideration of the European Utility Requirements (EUR) (see the EUR website) and of their proposed procedures suggests a general adequacy: *"As an example, if we consider the approach for design optimization against risks as presented in the European Utility Requirements (EUR), the specific risks associated with the coupling may be taken into account without modification of the design procedure as proposed on the figure below (integration to the risk analysis) [the figure is not included in this report]." (ibid.)*
- Considering the objectives in terms of Core Melt Frequency (CMF), a procedure is sketched to evaluate the impact of the external events induced by the industrial plant, assuring compatibility with the stated objectives. *"So, given the annual frequency of external events induced by the process plant, it should be demonstrated that the impact of the external events on the CMF remains compatible with the above limits." (ibid.)* It is also required that *"The risks induced by the coupled process should not exceed the range of radiological risks associated with the internal accidents of the nuclear plant." (ibid.)*
- The Defence in Depth (DiD) approach applied for LWR should be applicable also to the HTR plant and to the coupled system as well.
- For containment of radioactivity, the third barrier (meaning the containment system) can be reconsidered to be extended to allow for the separation of the NPP from the industrial process. A tentative scheme of the barriers for the coupled system is proposed.

Two test cases are also proposed: 1) Steam and electricity production in the Chemelot site (in the Netherlands); 2) Hydrogen production based on High Temperature Electrolysis (HTE). Schemes are proposed for the two test cases. In the case of hydrogen production, also Solid Oxide Electrolytic Cells (SOEC) have been considered.

The analysis of the test cases is somehow less relevant for TANDEM purposes, since they are relating to the specific HTR applications, though it may be taken as an example for similar analyses to be conducted for the LW-SMR. After this analysis, the issue of the flexibility of the nuclear plant required by the "end user" is addressed. In particular, the following is stated:

"A major challenge is to demonstrate the ability of the nuclear plant to follow the variations of the energy demand of the processes without being too much affected by the transients induced. This requirement applies to both test cases defined above. Practically, different time scales need to be considered to cope with the variations in energy demand:

1. over several years, the availability of the nuclear plant has to fit with the maintenance periods and the seasonal variations of the market,

2. over several days, the system has to follow the variation of the demand associated with schedule,
3. over several minutes, the system has to cope with peak demand or inadvertent shut down of the processes" (ibid.)

Though these aspects are not directly related to safety, it is clear that they may influence it anyway, e.g., by dictating the pace at which maintenance is performed in the NPP and affecting the possible Anticipated Operational Occurrences (AOOs) as a consequence of interfacing the nuclear reactor with the industrial process.

Chapter 5 is devoted to *the potential impacts of the industrial facility on the NPP*. The following main considerations in the chapter are here highlighted.

- Incident and accident events having a "direct" or "indirect" impact on the third barrier must be considered. Also, events that may damage the second barrier owing to transients imposed by the industrial process must be considered, as well as possible effects on the operational capacity of workers owing to toxic releases or effects on auxiliary systems. ([2])
- Considered events possibly occurring in the industrial plant are: Jet or pool fire; Vapour Cloud Explosion (VCE); Boiling Liquid Expanding Vapour Explosion (BLEVE); toxic substance dispersion.
- Probabilistic and deterministic approaches should be applied in this step. The Seveso risk directive is mentioned for regulating the risks in the industrial plant.
- It is mentioned that the European HYSAFE Network (www.hysafe.org/) issues a comprehensive Biennial Report on Hydrogen Safety describing the most important phenomena to be considered.
- Exemplary risk assessments are proposed for the Chemelot site and the HTE case.
- A full subsection on "Potential external impact on the nuclear plant" is provided in the report. In this regard, a TSO opinion suggests the following for an acceptable nuclear site safety demonstration:
  - *"The site of the nuclear plant is chosen to be as far as possible from any hazardous human activity (especially from stationary sources of hazards).*

([2]) A clarification must be introduced about the numbering of the barriers. In the considered document, apparently, the first, second and third barrier are the fuel, the reactor coolant boundary and the containment system. Generally speaking for LWRs, some early IAEA documents (e.g., INSAG-12) indicate four barriers being the fuel matrix, the fuel rod cladding, the primary coolant boundary and the confinement (i.e., containment). The constructive difference of different reactor types plays a role in this respect.

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- *A set of standard deterministic requirements are applied for the design of the barriers and the protection of the safety functions (external pressure wave, heat wave, etc.).*
- *External hazards are listed and grouped into families (explosions, toxics, etc.), for which envelopes are determined.*
- *The expected frequencies of external hazards (including those induced by mobile sources) are evaluated and compared to acceptance criteria.*
- *If the acceptance criteria are not fulfilled, the design of the nuclear plant is adapted to avoid any significant effect on safety functions, assuming a shutdown of the plant. Safety margins are to be demonstrated to avoid cliff effects (i.e., by sensitivity analysis)."* (ibid.)

- Two main questions are proposed, trying answers possibly valid at the time of the study and that should be reconsidered in the frame of TANDEM:
  1. *"Is there a common basis (means "widely accepted by the Safety Authorities") for the nuclear plant safety assessment with regards to the external hazards?*
  2. *Is the methodology used to characterize the industrial risks compatible with the safety assessment of the coupled system?"* (ibid.)
- The concept of "safety distance", as granting a zero risk beyond it, is critically considered. E.g., for the Chemelot site a safety distance of 2800 m is proposed on the basis of consideration of a storage tank explosion. Considerations are made also for the HTE case.

- Conclusions are drawn from the analysis performed in Chapter 5 and applications to the two test cases are proposed. It is suggested a full reading of this part of the report to consider possible similarities with the work to be performed in the frame of TANDEM.

Likewise, Chapter 6 is devoted to *the potential impact of the nuclear plant on the industrial site*. The following main considerations are here highlighted, suggesting again a full reading of this part of the report.

- The favourable safety characteristics of (V)HTR are obviously considered as positive aspects (inertia, low power density, passivity). Specific considerations applicable to (V)HTR are proposed.
- An intermediate heat exchanger (IHX) is considered in order to separate the NPP from the process.
- The restriction of all the possible consequences of accidents to the NPP site decreases the impact on the industrial site.

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- The issue of tritium production (e.g., from ternary fission, boron, lithium and graphite capture of neutrons, and activation of He^3) is considered, also owing to the capability of tritium to penetrate barriers.
- Considerations on the application of radiation protection principles.
- Specific considerations for the two test cases are proposed.
- The loss of the NPP heat source must be considered for the impact on the industrial process.
- The emergency plan must be made in combination for the two sites (nuclear and non-nuclear).

Conclusions and recommendations are finally drawn in Chapter 7 on the feasibility of the safety assessment of the coupled system. This chapter is quite interesting in the purposes of TANDEM and it is suggested that the entire report is considered as a guideline for setting up the methodology of safety assessment to be sketched in the frame of TANDEM for a LWR SMR.

In the Final Report Summary of the EUROPAIRS Project , the section on safety summarises the main conclusions as follows.

"Safety analysis

In parallel to the viability assessment, WP2 deals with safety and licensing issues arising from the coupling of the HTR with the heat process: events on one plant of the coupling will impact the other plant. The study identifies for some cases the specific risks that could arise and then put forward principles and tentative acceptance criteria for the feasibility of the licensing of the coupled system. The main requirement to ensure the safety assessment feasibility is that the safety of the nuclear plant shall not be negatively influenced by the coupling in comparison with stand-alone current nuclear installations. Moreover, feedback of recent safety assessments of nuclear installations sited close to industrial complexes was used for this analysis.

Another item reviewed by EUROPAIRS is related to potential contamination of the heat transport circuit between reactor and end-user by radioactive elements in general and tritium in particular. Indeed, several technical measures enable to reduce radioactive contamination of this circuit below currently applicable effluent limits. Previous experience is available from earlier HTGRs and from fusion reactor experiments, but construction of a nuclear cogeneration demonstrator will require the formal establishment of contamination limits in heat transport circuits, end user processes and products.

A review of the technical aspects of tritium contamination management is underway to provide elements on the available countermeasures to efficiently limit tritium contamination of the process. Given the limitations and principles laid down in the European regulation the

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analysis sketches the requirements to achieve an acceptable safety demonstration." (from Final Report Summary of EUROPAIRS)

Indeed, as already noted, the work performed in the frame of the EUROPAIRS Project, though targeted to the deployment of HTRs or (V)HTRs, represents an example to be carefully considered in the frame of TANDEM in order to develop the methodology requested in WP4 for assessing the potential resulting impacts on safety of cogeneration.

A further document that was considered in the survey is a literature publication on the EUROPAIRS Project that summarises the project objectives and purposes (Angulo et al., 2012).

2.1.2 Information from the NC2I-R Project

In the NC2I-R project, WP3 was related to *Safety and Licensing*. This work package *"provided input to WP4 regarding the licensing process, safety requirements and R&D needs to support the safety demonstration of a nuclear co-generation system."* (NC2I-R Final Report Summary). As main outcome, *"a tentative roadmap for the licensing of a co-generation system has been written, which aimed at giving a starting point to some European countries foreseen as potential hosts for a future demonstrator."* (ibid.)

The Final Publishable Summary of the NC2I-R Project (see Bibliography) represents another interesting example for the work to be performed in the frame of the TANDEM Project. Some of the concerns already discussed above for the EUROPAIRS project are revisited in the document and further considerations are added.

A review of the licensing feedback gained on past projects and existing nuclear cogeneration installations was made in the project. *"The review has showed that no cogeneration specific safety issue was raised during the licensing and operation of these installations which were mainly dedicated to low temperature water/steam production for district heating and industrial use. […] Finally, operators of the reviewed installations generally demonstrate that they have precluded the risk of radioactive contamination of the heat carrier fluid delivered to customers. Moreover, the strategy applied by the designers is to eliminate any potential impact on the neighbourhood in any situation."* (ibid.) These statements already suggest answers to some of the questions commonly raised by the coupling of plants in cogeneration.

An indirect coupling of the nuclear reactor to the industrial process is suggested, considering less feasible approaches where, e.g., dangerous products are produced in the reactor building. However, the licensing of an HTR prototype in cogeneration requires a detailed study of safety cases and the application of up-to-date licensing criteria. The peculiar features of HTRs are considered for suggesting a possible reduction of the exclusion zone.

In relation to the possible contamination of the steam produced by the nuclear plant owing to radioactive products, the idea of a third barrier as suggested in EUROPAIRS is supported. The specific R&D needs are considered mainly concerning the HTR case. On the issue of the “minimum distance”, it is stated that the nuclear reactor and the conventional one should not influence each other; however, since a limited distance needs to be used for practical reasons, related hazards could [or better should] be attentively considered.

For the impact on the conventional plant of the nuclear one, it is relied on the passive safety characteristics of HTR possibly suggesting a smaller exclusion zone with respect to LWRs. Radionuclide release limits may be affected by the transport of the linking means: there is a need to reconsider them. Concerning the thermal-hydraulic feedback/transients, the link with the conventional plant in this regard must be studied and reported in the Safety Analysis Report (SAR).

2.1.3 Information from the GEMINI+ Project

The structure of the GEMINI+ project is reported in different sources (see e.g., Wrochna et al., 2020) and is as follows:

- **WP1** concerned the licensing of a High Temperature Gas Reactor (HTGR) coupled with industrial facilities, with a safety design fully relying on intrinsic safety features of a modular HTGR;
- **WP2** elaborated the best design options for the HTGR system complying with the outcomes of WP1 and taking into account also economic aspects of modular reactors;
- **WP3** considered several innovations in different fields (e.g., material, industrial processes and so on) and assessed the benefits that such innovation would bring to a HTGR system in cogeneration mode;
- **WP4** addressed the conditions for the implementation of a demonstration plant in Poland, considering availability of a reliable supply chain for the components and a business plan to define funding;
- **WP5** aimed to create a favorable environment to deploy the demonstration plant in, e.g., via support to industry through a Business Advisory Group or support to competence building of a Polish team on HTGR technology.

The project deliverables that were considered for this survey are the D2.2 - Final requirements, assumptions and constraints for GEMINI+ high temperature nuclear cogeneration system (Lavarenne, 2019), the D.1.3 – Updated safety requirements for an HTGR for nuclear cogeneration, the D3.7 - Use of HTGR process heat for nitrogen fertilizers and chemical products

(Pabarcius, 2018) and D3.14 - Feasibility of realistic load following with HTGR in cogeneration mode (Mull and Herr, 2020). The paper by Wrochna et al. (2020) is related to both NC2I-R and GEMINI+ Projects and represents a reflection on the basis of the work of both projects on nuclear cogeneration with HTGR reactors.

*"**Deliverable 2.2** provides high-level requirements for the GEMINI+ project specifically as well as, more generally, for a European HTR project."* (Lavarenne, 2019). The requirements are of a general nature. Some of those related to safety are listed hereafter.

- *"The coupling shall ensure adequate separation between the nuclear licensed reactor side and the industrial process (steam) plant."* (ibid.)
- Load following capabilities of heat production should be from 30 to 80% at a rate of 10% per hour and from 80% to 100% at the rate of 5% per hour;
- *"The HTR plant should be designed to continue operation during a complete loss of process heat load demand and stabilize in the electricity generation mode."* (ibid.)
- Allowance for operation transitions must be included
- The HTR should be able to provide electricity and process heat
- Specific criteria for energy production are provided: full load rejection should be tolerated
- DiD, Exclusion Area and Passivity are mentioned, inter alia
- Core melt should be physically impossible.

General recommendations are proposed for the independence of the process and the plant against possible contamination of interfacing fluids and the possible hazards created to the NPP from the process. *"It shall be demonstrated that the external hazards potentially induced by the industrial environment may not degrade the safety functions of the nuclear plant. For that purpose, priority is given to the establishment of a safe distance between the nuclear plant and the coupled facilities."* (ibid.). Some requirements are specific of the Polish situation.

Deliverable D1.3 (Baudrand et al., 2020), adopts the TSO perspective to propose HTR design requirements compatible with international standards. The work was based on the analysis of the IAEA SSR 2/1 rev.1, which is a guide for LWR plant designers. In the deliverable, some complements are suggested, addressing multi-unit configuration cogeneration, which may be of interest for the TANDEM application. In particular, it was proposed to complete the SSR 2/1 requirement No. 33 (Safety systems, and safety features for design extension conditions, of a multiple unit ([3]) nuclear power plant) as follows:

"*The modular configuration could most likely involve the sharing of systems and services between several modules (e.g., ventilation, service water circuits, fire detection, etc.). Multi-unit sites could rather involve the sharing of external services and mobile equipment used as "safety features" for design extension conditions. However, the systems performing the safety functions for each module shall be independent. The licensee shall take into account the risk of common mode failure by adequate design, physical separation and, as far as possible, diversification of equipment.*

Common cause failures (i.e., potential for failures affecting several modules simultaneously) should be assessed for multi-unit sites and modular reactors. In particular, equipment that would be used to prevent or mitigate accidents equally on all units or modules (e.g., mobile emergency power generators, pumps, etc.) shall be designed to be able to cope with multiple module failures. Adequate capacity and availability of this equipment shall be demonstrated. Likewise, the potential risk associated with a shared control room shall be minimized. If the third barrier of confinement is common to several reactor modules, it should be designed to cope with the consequences of potential common mode failures of the second barrier.

The licensee shall ensure the availability of enough human resources to manage accidents on multi-units or multi-modules configurations." (Baudrand et al., 2020)

It is also proposed to amend requirement No. 35, taking into account the potential for cogeneration of electricity and heat for industrial applications:

"*To ensure acceptability of the coupling scheme in European countries, it shall be requested that the fluid delivered to the customer be free of artificial radioactive elements (i.e. radioactive elements coming from the reactor). In that frame, following technical requirements can be detailed:*

- At least three barriers should be established between the fuel and the fluid delivered to the customer.
- Isolation devices should be implemented in the secondary circuit and in the customer circuit.
- Provisions should be taken for early detection of potential contamination of secondary circuit.

([3]) In the deliverable, consistently with the definitions adopted by the SMR Forum, distinction is made between multiple units (several nuclear plant units on the same site) and multiple module architecture (several identical reactors in the same building).

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- Adequate pressure staggering should be established between the fluid delivered to the customer and the primary helium in order to prevent leakage from primary helium to secondary fluid and customer fluid." (ibid.)

Deliverable D3.7 (Pabarcius, 2018) refers to chemical applications for nitrogen fertilizers as a connected industrial process. Steam is provided by the HTR, requiring a line for transfer.

"The concept of coupling nuclear unit with industrial site need to ensure very high reliability on availability, stable steam parameters, high level usage of existing infrastructure on industrial site as well as competitive economic factors." (Pabarcius, 2018)

The panorama of chemical producers in Europe is revised for needs. E.g., powers in the range of 100-200 MWTh seem to be most requested. Fertilizer production is an energy intensive sector. A few excerpts from the text are worth being reported hereafter.

> *"The location of nuclear facility close to the industry site is desired. However, the siting issue should be oriented to choose remote, but accessible, locations to mitigate any consequences of any accident"* (ibid.)
>
> *"It should be noted that because of the passive safety characteristics of HTRs, low power density and consequential elimination of scenarios comparable to LWR core melting scenarios, the derived HTR exclusion zone is smaller than for other NPP types, allowing a closer distance to the end user facility or other public infrastructure (schools, stadium, etc.)."* (ibid.)
>
> *"The HTR and the industrial end user facility shall not influence each other in particular in case of BDBA on the chemical site, such as explosions or release of corrosive materials."* (ibid.)
>
> *"The safety related risk by external hazards for the HTR shall be independent from the cogeneration components and the end user facility."* (ibid.)
>
> *"For fertilizer (ammonia) plants the specific high risks are: fire and explosion hazards resulting from the leakage of flammable materials, and detonation pressure wave"* (ibid.)
>
> *"Any single failure of one system should not weaken the safety of the other. In particular, the defence in depth shall call for appropriate protective barriers against any radioactive transfer from the nuclear to the industrial site"* (ibid.)
>
> *"It is required to define a specific area, additional barrier, with special security treatment around facilities and plants, being sources of effect on life environment and health (referred to as the sanitary protection zone SPZ) the size of which ensures reducing of air pollution (chemical, biological, physical) up to the values established by the national sanitary-hygienic standards. Usually, nuclear site protection zone area requirements fulfil the ones defined for industrial site."* (ibid.)

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> *"The pollution caused by industrial site outside the SPZ must not exceed the threshold values established in the legislation on the public and recreation environment."* (ibid.)
>
> *"The supply of steam to an industrial process by a nuclear plant generally implies the need to have the nuclear facility in close proximity to the industrial process to reduce transmission line costs. Distance between the industrial site and HTR unit should assure safe operation for both units and at the same time not cause extensive heat and/or pressure losses at long distances. It was pointed out that a 2 km distance is sufficient to prevent hazards from industrial site to affect HTR."* (ibid.)
>
> *"The direct coupling between the secondary circuit and the industrial heat process seems to be very simple. However, it might not be acceptable from the point of view of tritium release and the contamination of industrial equipment."* (ibid.)

Deliverable D3.14 (Muller and Herr, 2020) *"[…] investigates if and how a cogeneration HTGR can meet a number of requirements which are likely to be expected from SMRs in flexible future energy system. On the one hand there is the need to give best way to the power requests from the industrial end user without inacceptable changes of the nuclear fission power production. On the other hand there is the aspiration of integration into energy systems with an increased proportion of intermittent renewables or fluctuating demand (hybrid energy system). Beyond adaptations of the fission power of the nuclear reactor, which should be minimized, the options could be temporary energy storage (in the form of heat, hydrogen or hydrogen derivatives) or load following by flexible sharing of secondary steam between the turbine and poly-generation, while keeping the nuclear reactor itself operating at constant power."* (ibid.)

Again, a few verbatim excerpts from the report suggest some of the leading ideas.

> *"The near term industrial applications that extend the use of nuclear energy for non-electric missions have been shown to be primarily directed toward providing co-generated process heat in the form of steam and electricity:*
>
> - *Cogeneration supply of electricity and steam to major industrial processes in petrochemical, ammonia and fertilizer plants, refineries and other industrial plants.*
> - *Hydrogen production and supply to industrial plants and to the merchant hydrogen market.*
> - *Electricity generation for micro grids and load-following."*
>
> *"The HTGR for cogeneration shall have load-follow capability. Reactor module power level and steam production shall be increased or decreased relatively easily. Systems shall also shift energy between electricity generation and heat supply dynamically as load conditions vary, all while keeping the reactor power constant."* (ibid.)

The needs for process heat are revised considering the different temperature level uses. The control system of the whole plant and its levels are also considered for the application of HTGR in cogeneration.

In order to set the reference operating conditions, different scenarios of coupling are proposed:

- Reactor operating at 100% power at 180 MWth with 165 MWth for the end-user process and 15 MWth for electricity production;
- Reactor operating at 100% power at 180 MWth with 135 MWth for the end-user process and 45 MWth for electricity production;
- Reactor operating at 25% (i.e., 45 MWth) with all the power used for the end-user (no electricity);
- Reactor operating at 25% (i.e., 45 MWth) with all the power used for electricity (no end-user power).

Transients between each one of these states and the others are considered. No numerical result is provided in the report for these cases that also include the possibility of turbine trip and other postulated events.

The discussion expands on the load and operational flexibility of the HTR-module.

> *"The HTGR module is capable of providing primary frequency control (automatic power modulation based on external frequency control signal). However, load following and flexible operation is best economically achieved by load balancing capability of the HTGR module. The primary purpose of the HTGR module is production of high temperature steam for industrial application. Electricity generation is added income stream to increase the flexibility of plant operations and economics."* (ibid.)

The above consideration matches with obvious worries for the fact that by adopting a load following strategy, the safety of the reactor under such operating regime will need to be rediscussed (e.g., in front of known problems related to fuel and equipment damage for power cycling) and the economic aspects will worsen in a situation in which economic feasibility of a new application must be demonstrated.

The final chapter discusses the feasibility of smart grids and the related market needs. Technical aspects of load following in French LWRs are also shortly presented. This issue will be discussed in commenting other reports later on.

The **paper by Wrochna et al. (2020)**, being related to both NC2I-R and GEMINI+ projects, also highlights interesting aspects of the work performed in the last decade in the NC2I environment. Again, a few verbatim excerpts of the text are useful to grab some key concepts.

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> *"Clean energy production is a challenge, which was so far addressed mainly in the electric power sector. More energy is needed in the form of heat for both district heating and industry. Nuclear power is the only technology fulfilling all 3 sustainability dimensions, namely economy, security of supply and environment. In this context, the European Nuclear Cogeneration Industrial Initiative (NC2I) has launched the projects NC2I-R and GEMINI+ aiming to prepare the deployment of High Temperature Gas-cooled Reactors (HTGR) for this purpose."* (Wrochna et al., 2020)

> *"In Europe, about 89 GWth, i.e., 50% of the process heat market is found in the temperature range up to 550 °C (today mainly in the chemical industry, in the future possibly in steelmaking, hydrogen production, etc.)"* (ibid.)

As a comment to this excerpt, it can be noted that for the TANDEM Project a similar inquiry about the needs for heat at temperatures in the range of those envisaged for LW-SMRs should be made, in order to identify the specific industrial needs and the related market. The paper also details the system requirements with reference to Poland and to the conceptual design of the HTGR reactor.

An interesting safety aspect is then mentioned. *"Even if the modular HTGR does not require electric power supply to be kept in safe conditions, keeping the reactor available to supply steam to the steam network requires continuing reactor operation even in case of loss of external power supply. A small turbo-generator located in the secondary circuit will therefore generate the power required for the house load of the nuclear plant, and the thermal power required to produce the steam branched off to the internal turbine is estimated to be about 15 – 20 MWth ."* (ibid.)

The issues of continuity in heat production by the NPP to supply the connected industrial process and, viceversa, of continuity of electricity production on the grid to supply off-site power to the plant seem to be crucial ones. The latter will be stressed more below in commenting information found in international work on the subject of hybrid nuclear and renewable energy systems.

... /...

In closing this section on the information drawn from the three mentioned European projects, it can be noted that in the field of development of high temperature and very high temperature nuclear reactors (HTR and (V)HTR) cogeneration and its safety implications have been targeted repeatedly, highlighting aspects of interest also for LW-SMRs, being the subject of TANDEM. The physical and operational differences between HTRs and LWRs will indicate the changes that the conclusions reached in the NC2I frame will need to be adapted to the LWR case. Indeed, the range of temperatures for the process heat are lower and this will condition the technology to be used, e.g., for hydrogen production.

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Several times in the above reported discussions it is stressed the need for a safety assessment of the combined cogenerating system. This request will guide the developments to be made under TANDEM that, though inheriting concepts and ideas already explored by NC2I in its projects, will suitably adapt and customise them for the addressed cogenerating scenarios, including multi-unit LW-SMRs.

2.2 Selected information from available literature

During the phase of collection of information from TSOs and Partners, some first indications of possibly useful material were received. At the same time, the University of Pisa performed an own screening of literature, completing a reasonable review of available material.

Though it was not easy to find documents fully suitable for LW-SMRs in cogeneration combinations, it was later recognised that the received suggestions could at least provide valuable information for discussing the issues of direct relevance for TANDEM in its own context.

The different sources are presented hereafter, often in the form of a reading guide. It must be noted that this collection cannot be considered exhaustive, but it represents the useful information that it was possible to gather from the work of the group to put the first basis of the envisaged methodology for the assessment of safety margins. A summary of the main discussed aspects will be reported in the next subsection.

Application of the results of the second stage of the SMR Regulators Forum within the framework of licensing SMR projects in Ukraine, Igorevich et al. (2022)

This recent paper by Igorevich et al. (2022) discusses the applicability and sufficiency of the existing regulatory framework for SMRs. The issue of the possible relaxation of regulatory requirements with respect to large scale reactors, advocated by SMR proposers, is discussed. The report by the SMR Regulators' Forum (2018) is mentioned in regard, as containing the developed common regulatory positions on these aspects. It is suggested to avoid relaxing safety criteria for the first SMRs in the series, asking on the contrary additional requirements to confirm their safety characteristics. Safety issues brought about by multi-modularity are also discussed, e.g., in relation to sequential deployment of units and use of shared structures.

As said, the aspect of the *graded approach* for the application of regulatory requirements to SMRs is analysed in the report by SMR Regulators' Forum (2018): though several interesting issues related to defence-in-depth and emergency planning zone, having relevance for cogeneration aspects, are discussed, no specific mention of hybrid systems is made.

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Nevertheless, in the purpose of TANDEM this report is valuable, together with similar information that can be found in literature, to compare the risks from HTRs and LWRs, in order to consider the applicability to the latter reactors of considerations about cogeneration developed for the former.

Potential of Cogeneration Fast Reactors, ESNII plus – D4.31

This ESNII+ report by Roelofs et al. (2016) is targeted to the discussion of cogeneration in fast reactors; as such it is not directly pertinent for the specific discussion of cogeneration in LW-SMR, though it has aspects of indirect interest. In particular, Chapter 2 discusses the cogeneration market for fast reactors based on assessments made for nuclear cogeneration more in general. Chapter 3 links the nuclear fast reactor systems and the cogeneration applications; the synergy with cogeneration of SMRs and Advanced Modular Reactors (AMRs) is highlighted. Chapter 4 provides a top-down cost estimate for a cogeneration fast reactor based on the cost estimate prepared for ESNII+ task 4.2 for a small modular fast reactor. The report is quite detailed and interesting in assessing the different aspects of the problem.

In Section 3.2 (Recommendations to System Specification and Requirements), system architecture general guidelines to ensure the availability and reliability of the thermal power source, as well as some interesting safety and licensing aspects are also covered as follows.

"(…) The combination of a highly reliable heat source and the availability of reserve capacity is the key to meet the availability requirements of industrial end-users. A common solution is to construct multiple small units which back-up each other, or to complement the nuclear heat source by a conventional process heat source. (…) Consequently, as for fossil-fuelled heat sources, redundancy is needed. Multiple unit cogeneration power plants, modular designs, or back-up heat sources are suitable solutions.

The above considerations, combined with typical strategies to improve system availability, can drive the following recommendations and specifications:

- The heat source shall be sufficiently redundant. Possible means are:
- Modularization of the nuclear heat source, through multiple units of smaller size (unit sizes corresponding to only a fraction of the overall peak load);
- Diversification of the heat source, through back-up conventional fossil-fired boilers of minimum acceptable capacity, in hot standby.
- A reserve capacity shall be foreseen in order to meet any transient operation potentially occurring as a consequence of a fault.

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- The Systems Structures and Components (SSCs) interfacing the heat source and the process heat distribution network shall be sufficiently redundant. Wherever possible,
- Proven technology and standard components (characterized by available reliability data) shall be used;
- Common cause failures to redundant components shall be avoided;
- Spare parts for critical components shall be considered to minimize the down-time (taking into account also costs, space requirements, shelf-life,…)
- De-rating strategy (i.e., operation of a device at less than its rated maximum capability in order to prolong its life) shall be applied to active components;
- The level of redundancy shall account for the requirements of periodic maintenance.
- Periodic maintenance (including inspection and testing) shall be guaranteed on a regular basis, without entering into conflict with the nuclear power plant operations. In particular,
- Any maintenance and inspection operation shall be favoured in terms of layout (accessibility, lay-down space, routing of components,…);
- Monitoring and diagnostic systems shall be installed to promptly identify deviations from reference operating conditions, and, possibly, predict malfunctioning.

Specific requirements and design options are typically considered on a case by case basis and subject to trade-off analyses, supported by adequate methods and techniques to model availability of a complex system (e.g. fault tree analysis)." (Roelofs et al., 2016)

"*The use of nuclear energy for process heat applications has to be carefully evaluated from a safety point of view. Additional safety design requirements (in terms of prevention and* mitigation) may derive from considerations related to postulated initiating events:

- affecting specific Systems Structures and Components (SSCs) interfacing the NPP with the end user, or
- induced by the end user of the process heat and potentially affecting the NPP.

Moreover, the licensing procedures may need to be adapted considering the site co-sharing or the short distances between the nuclear site and the end user (industrial site). Lessons can be learned from experience in applications of nuclear cogeneration for process heat for industrial purposes gained, inter alia, in Canada, Germany, Norway, Switzerland, India and Russia. Even more countries have been using nuclear power as a heat source for district heating or desalination. (…)

Most non-electrical applications of nuclear power are based on steam bleeding from steam turbines, delivered to specifically designed heat exchangers coupled with the steam distribution network. The primary circuit is typically separated from the heat grid by at least two physical barriers. The system is also provided with isolation equipment and monitoring devices to control the delivered fluid (tritium migration could represent a safety concern).

Typically, the amount of thermal power diverted to the cogeneration application is limited (in the order to 5 to 10%), thus having a limited impact on the control of the NPP. Increasing this value *may turn into initiating events induced by the heat grid or the end user onto the NPP (i.e. thermal load rejection), which need to be carefully evaluated and categorized as design basis events. Therefore, the reliability of the network and of the end user could play a role in the NPP safety assessment. The proximity or co-sharing of the nuclear and the industrial sites has a two-folds effect. In case of a nuclear accident, the compatibility of the implementation of protective measures against radiological consequences staff (e.g., sheltering or evacuation) with the requirements of industrial facility (e.g. continuous monitoring or insufficient time for emergency shutdown) need to be assessed. On the other hand, the accidents potentially affecting the industrial site (e.g. chemical reactions, explosions, airborne toxic releases, impact on heat sink,…) close to a radiological barrier, as well as potential domino effects, have to be considered as external hazards during the NPP safety assessment. (…)*

The above considerations can be preliminarily translated into a list of technology-independent design recommendations for the process heat system (i.e. those SSCs having the function of transferring process heat to the end user distribution network):

- The process heat system shall be provided with provisions to practically eliminate the risk of noticeable contamination of the delivered fluid. In particular,
- At least two confinement barriers shall be ensured between the primary system and the conventional network system.
- Pressure shall increase from the primary system towards the end user in order to guarantee in-leakages from less contaminated fluids towards more contaminated ones.
- Monitoring of the intermediate and final thermal vectors shall be ensured continuously.
- Provisions shall allow for timely isolation, in case radiological contamination limits are exceeded.
- The process heat system shall be designed to ensure that the appropriate design limits of the primary system are not exceeded in operational states or in accident conditions. Consequences induced on the primary system by events occurring on the end-user side (including distribution network) should be preferably avoided or properly controlled (depending on occurrence frequencies).In particular,
- Rated and qualified systems shall ensure regulation capabilities to allow for flexibility (e.g., heat demand variations), up to full isolation under specified conditions (e.g., load rejection).
- The steam supply and feed-water systems (to and from the heat process system) shall be of sufficient capacity and shall be designed to prevent anticipated operational occurrences from escalating to accident conditions.
- Combined events affecting both the process heat system and electrical generation systems shall be considered and properly managed.
- Risks induced by the vicinity of industrial facilities shall not lessen significantly the nuclear plant safety. In particular,

- Additional man induced hazards shall be considered in the safety demonstration.
- External hazards potentially affecting both installations shall not induce escalation effects (e.g., common impact on heat sink).
- The minimum distance between the nuclear island and the industrial site shall be assessed taking into account the additional generic hazards induced by the industrial installation (e.g., plume, explosions, fire,…).
- In case of nuclear accidents with off-site consequences, adequate emergency measures shall be defined taking into account requirements from affected industrial installations.
- Protective measures due to large radioactive releases affecting the area of the industrial installation shall be limited in time.
- *Time to implement* emergency measures due to early radioactive releases shall be compatible with safe operation of the industrial installation.

Above considerations shall be considered as preliminary design recommendations or guidelines, which shall be further developed into more structured design criteria and requirements. Safety cases shall include justification for specific design options and choices in order to demonstrate the safety of the installation. Risks induced by cogeneration and specific industrial environment shall clearly appear in the siting and licensing documents (e.g., environmental impact assessment, security plan, emergency preparedness plan)." (Ibid.))

These considerations reinforce and better specify concepts already introduced speaking of NC2I projects.

Applicability of Safety Objectives to SMRs, WENRA Report (2021)

In 2021, the Western European Nuclear Regulators Association (WENRA) issued this report (WENRA, 2021) on the applicability of the safety objectives discussed in a more general fashion for "new" NPPs in an earlier report (WENRA, 2013). Though even this report by WENRA does not address specifically the aspects related to cogeneration and hybrid systems, it offers anyway interesting suggestions pertinent to the present discussion. In principle, SMRs are "new" NPPs, and the safety objectives discussed in WENRA (2013) should be applicable to them as well; however, *"[…] it was considered beneficial to study them from the point of view of SMRs to confirm the applicability and to identify potential questions that would benefit from further study or guidance."* (WENRA, 2021). Firstly, the different SMRs are distinguished in categories as Large-scale SMRs (300 MWe /~1000 MWth), Medium-scale SMRs (50 MWe /~150 MWth) and Small-scale SMRs (10 MWe / ~30 MWth). A more interesting classification is then related to the destination of use:

- "Centralized medium to large-scale units intended as an alternative to current NPPs with a large local infrastructure base.

- Local small to medium-scale units intended for local use in populated areas, such as larger cities or large fabrication facilities with medium-sized localized infrastructure.
- Remote small-scale units intended for remote deployment with minimum infrastructure and personnel." (ibid.)

Some physical characteristics are then reviewed, as low power, novel measures to enhance safety, partially different or missing initiating events, long grace periods, challenges for periodic inspection for integrated designs, unconventional number of physical barriers, use of novel fuels, high degree of automation, shared use of common systems, structures, components (SSC) between several cores, unconventional siting (underground, sea-bed, remote locations, off-grid locations), factory fuelled cores, initial testing shifted to factory, new companies as developers and utilities. Among these features some may be beneficial or detrimental to safety and the focus is put on multi-unit aspects, requiring specific safety assessment for common mode failures and the sharing of common structures, as the control room. Serial production and modularity are other two aspects considered, also in relation to the fact that testing responsibility may be shifted to the constructor instead of being on the shoulders of the licensee. Indeed, many of these aspects differentiate SMRs from large NPPs for which well-established safety assessment procedures and routine practices do exist.

Chapter 3 of the report is particularly interesting because it is focused on the applicability of each one of the WENRA Safety Objectives to SMRs. The first safety objective is particularly interesting for our discussion, being formulated as: O1. Normal operation, abnormal events and prevention of accidents. In the report it is detailed as:

- "reducing the frequencies of abnormal events by enhancing plant capability to stay within normal operation;
- reducing the potential for escalation to accident situations by enhancing plant capability to control abnormal events." (ibid.)

Besides some SMR characteristics which are considered beneficial for safety, it is noted that *"novel and innovative solutions may induce unexpected disturbances in the early phase before operating experience is accumulated and the reactor design and mode of operation evolves accordingly"* (ibid.) In our context of cogeneration, it is clear that these "unexpected disturbances" will come also from the interaction between the plant and the served industrial process; experience should be accumulated at a level comparable to the one available for large NPPs before declaring a satisfactory safety level of cogenerating SMR units.

The other listed objectives are: O2. Accidents without core melt; O3. Accidents with core melt; O4. Independence between all levels of defence-in-depth; O5. Safety and security interfaces; O6. Radiation protection and waste management; O7. Leadership and management for safety. At least at a first glance, it seems that these aspects may be more dependent on the particular type

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of SMR than on its collocation in a cogenerating system. However, cogeneration may have a specific influence on some of these aspects and a more in-depth assessment of each one of them is recommended. In particular, cogeneration may bring about differences in the management of the interfaces between safety and security, owing to the personnel and the software involved in managing both the nuclear and the non-nuclear infrastructures. Likewise, radiation protection of personnel involved in the non-nuclear infrastructure could be needed in case in which a complete separation between the two activities cannot be implemented by design, something that in general is not straightforward to demonstrate. As it will be shown later in this report, the list of safety objectives by WENRA can be useful also for an assessment of the safety margins impacted by cogeneration.

Another aspect highlighted in the WENRA (2021) report is the independence of the different levels of Defence in Depth (DiD), discussed in Appendix 1 of the report. The five levels of defence in depth are discussed in this view considering the characteristics of SMRs, including the quite positive ones claimed by different proponents. For instance, for Level 4 *"it is considered not to be feasible to practically eliminate severe accident conditions, unless core melt can be demonstrated to be physically impossible"* (ibid., Appendix 1). In summary, the WENRA (2021) report can be considered as a starting basis for further assessing how the safety margins and the safety objectives can be affected by cogeneration in different SMR concepts.

Small Modular Reactor Regulators' Forum Reports

A series of reports recently issued by the Small Modular Reactor Regulators' Forum was also considered, in addition to the one already mentioned above. These reports (Small Modular Reactor Regulators' Forum 2019, 2021, 2021a, 2021b) are devoted to various aspects and are written by the different Working Groups on "Safety Assessment", on "Licensing Issues" and on "Manufacturing Construction Commissioning and Operation". As known, *"The SMR Regulators' Forum was formed in 2014 to identify, improve understanding of and address key regulatory challenges that may emerge in future SMR regulatory discussions"* (Small Modular Reactor Regulators' Forum, 2021). Even these reports do not specifically address issues related to cogeneration, being focused on more general aspects related to the safety of the SMRs, to their licensing and constructability. Among the considered aspects, the following ones are given particular attention:

- multi-unit, multi-module aspects of SMRs;
- considerations in the use of passive and inherent safety features in SMR designs;
- aspects of Beyond Design Basis Analysis relevant to SMRs.

The first of the previous three items appears to be one in which the additional concerns related to cogeneration may certainly play a role. In fact, some aspects related to multi-unit arrangements of reactor modules can be affected by “external” perturbations coming from the industrial process coupled with the SMR nuclear energy production units. In particular, in Appendix B of the report a list of items influencing the Probabilistic Safety Assessment of multi-unit nuclear reactors are considered; for them, the following considerations are highlighted under the heading of “Selection of Initiating Events”:

- *“Many single-unit PSA-initiating events (e.g., loss of off-site power, loss of heat sink, external events) challenge multiple units;*
- *Need to delineate single unit/facility and multi-unit/facility events;*
- *Most external events involve multi-unit challenges;*
- *Extent of shared systems increases the importance of some internal initiating events (e.g., support system faults)”* (ibid.)

Considering that among the “external events” we may include the two-way interactions between the nuclear plant and the industrial process, it is clear the need to account for the effects of these external perturbations on the multi-unit structure of the SMR installation. The discussion in the report (ibid.) also highlights a list of issues addressed in general for SMRs, which, in our present purposes, could be useful to further discuss in view of cogeneration; these issues are:

- First of a Kind (FOAK) issues;
- Multi-unit/multi-module issues;
- Passive Safety;
- Exclusion of Faults from Safety Analysis;
- Severe Accidents and Design Extension Conditions.

As said the report is not focused on cogeneration aspects, so the above list can be considered in the purpose of the TANDEM Project to assess if, in addition to the discussion presented in the mentioned SMR Regulators’ Forum reports, further concerns brought about by cogeneration may appear.

ORNL Report on Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

The Oak Ridge National Laboratory (ORNL) report (Volume 1) by Ball and Fisher (2007) deals with the construction of a Phenomena Identification and Ranking Table (PIRT) to evaluate some of the most important phenomena that would impact the safety of a very high temperature reactor

(VHTR). The report may be taken as an example to set up a safety assessment process of small modular light water reactors. Among the various investigated phenomena, the coupling of a VHTR plant with a high-temperature hydrogen production plant is addressed (the latter is deepened in Vol. 6 of the same report, mentioned below). In this regard, several phenomena are identified that could directly affect the safety of the nuclear plant, including the release of gaseous chemicals from the plant. It is specified that a release of hydrogen is not as dangerous as the release of heavier gases such as oxygen, which is one of the products of electrolysis, as hydrogen is dispersed much more easily than oxygen owing to the much lower weight than the one of air. Another addressed topic is the possible malfunctioning or rupture of the heat exchanger interposed between the primary circuit and the chemical process. Nevertheless, in case of using a LW-SMR, the layout would be different as it should be the live steam of the secondary circuit to provide heat to the industrial process by means of a heat exchanger.

An interesting outcome that is mentioned in the report is that the safety requirements of a nuclear plant and a chemical plant are different. In the case of a nuclear power plant, indeed, it is tried to avoid releases in outdoor environments as much as possible. On the contrary, in a chemical plant one of the safety requirements relies on the construction of the components in open environments to avoid dangerous accumulation of pollutants. This could be a problem regarding the release of radioactive elements in accidental situations, because the philosophy for dealing with dangerous substances are so different in the nuclear and the cogenerating plant and the chemical plant can be directly exposed to radiation with little protection.

The Volume 6 of the same report (Forsberg et al., 2007) focuses on the safety analysis of the coupling between a VHTR and a hydrogen production plant, for which different technologies are considered. In the introductory part (Chapter 2) several interesting observations are reported.

- The hydrogen production plant is highly dependent on the operation of the nuclear plant, especially for a coupling in which a large percentage of the power produced by the reactor is used to generate hydrogen. In this case, the start-up and shutdown of the reactor and of the chemical process are highly interdependent. Furthermore, important transients that occur on the side of chemical processes could lead to the reactor SCRAM.
- The different safety philosophy adopted by a nuclear plant and a chemical plant makes it impossible to integrate the industrial process into the nuclear power plant. Another important aspect that must be considered in terms of safety consists in the different regulations of the two industrial plants and in the fact that, most probably, the operators of the two systems will be different.

Chapter 3 of the report, on the other hand, deals quite in detail with each phenomenon entered and evaluated in the PIRT. As in Volume 1, there are some aspects that are relevant only for the particular coupling envisioned between the VHTR and the industrial process, such as the fact that

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a failure in the intermediate exchanger (the one that communicates directly with the helium loop) could lead to tritium contamination of the intermediate circuit or to an unwanted mass ingress into the reactor.

Other described phenomena, however, could also be applied to light water reactors, at least after a due transposition to the LW-SMR technology, as detailed below.

Release of gaseous substances from the system. Among the various non-corrosive gaseous substances taken into consideration, the one that is given the greatest importance is oxygen, especially if at a relatively low temperature, since its release can cause a dense cloud that could move towards the nuclear power plant. Therefore, the height difference between the nuclear power plant and the hydrogen plant also becomes important. Emissions of corrosive substances typical of thermochemical cycles with acids are also investigated. These, however, do not seem to be of interest for water reactors given the high temperatures required. Other investigated emissions are flammable substances such as natural gas from steam reforming plants.

Breaks in the primary heat exchanger. In the case of a VHTR, a break in the primary heat exchanger would bring the intermediate circuit directly into contact with the reactor, with consequent danger of a loss of coolant.

Thermal transients of the industrial process which could influence the reactor. It is highlighted that if a liquid is used as the heat transfer fluid, the effects of transients in the chemical process on the nuclear reactor would have minor impact due to the low velocities of the fluid and to the higher thermal capacity. Moreover, storage devices could be placed in the intermediate circuit to damp transients.

Events initiated in the reactor inducing imbalances in the chemical process which, in turn, create a dangerous condition for the nuclear plant**.** They may be, for instance, thermal transients of the reactor due to the inadvertent insertion of control rods which would decrease the temperature of the primary system, leading to the shutdown of the chemical process which, in turn, would result in a loss of the heat sink of the reactor.

Opportunities for Cogeneration with Nuclear Energy, IAEA (2017)

This report, after highlighting some fundamental aspects of cogeneration in general and of its advantages in the present energy panorama, expands specifically on nuclear cogeneration, considering the different kinds of nuclear reactors that can be employed in relation to the intended applications. Three interesting tables list the nuclear reactors existing worldwide for cogeneration purposes, with main reference to sea water desalination, district heating and process heat generation. Since these reactors are operating and accumulating hundreds of reactor-years of experience, the analysis of the problems encountered and the related solutions applied in their design and management is useful to predict the issues to be coped with in the case of SMRs in similar applications.

After an excursus on different cogeneration applications and on their technical issues, Chapter 5 is devoted to safety considerations. A few excerpts from the text help in summarising the main message conveyed by the report in regard.

Site considerations

"In addition to the typical siting of nuclear plants, close location to the load centres is desired. However, the trend is to choose remote, but accessible, locations to mitigate any consequences of an accident. Siting far from densely populated areas makes it easier to comply with regulatory requirements. Furthermore, plants need to be near a ready supply of cooling water." (IAEA, 2017)

"Building a nuclear facility near industrial plants, which might also be near populated areas, requires additional considerations. Some potential issues include the following:

— Requirements for additional safety features;
— Plans for the safe and orderly shutdown of the industrial process and the sheltering or evacuation of industrial facility staff in the event of an accident;
— Detailed plans for public notification, sheltering or evacuation in the event of accidents;
—Increased requirements for public education and programmes encouraging public acceptance.

The specific requirements will be determined by the reactor type, the nature of the industrial process, the distances from the industrial facility and population centres, and prevailing public attitudes. A new generation of smaller reactors with passive safety features might at least partly mitigate some of these issues." (ibid.)

Specific consideration for water desalination plants follow, not discussed here.

System Coupling

"[…] coupling a nuclear heat source to any industrial process heat application can either be done with a heat transfer via an intermediate helium circuit from the reactor to the process heat plant, or with a heat transfer directly from a (nuclear grade) high temperature heat exchanging component in the primary circuit into the chemical process." (ibid.)

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"Most new concepts of nuclear process heat applications, however, are based on the concept of an intermediate circuit, in which heat from the secondary helium is transferred in a process heat exchanger to the industrial process." (ibid.)

"*Heat exchangers play an important role in the cycles, since they connect reactors and pipelines to transport reactants and allow for heat input or recovery. The need of an IHX for the decoupling between the primary circuit and the heat utilization system is given for the following reasons […]:*

— Separation of the nuclear island from the chemical plant reduces the risk of any safety related interactions.
— Limitation or exclusion of radioactive contamination of the product (e.g. tritium).
— Control on corrosive process media for the exclusion of ingress into the primary circuit.
— Near conventional design of heat utilization system with ease of maintenance and repair.
— Flexibility in system design (e.g. in the choice of coolants for the intermediate circuit)." (ibid.)

Pressure reversal, Monitoring, Tritium
Besides considerations on pressure reversal for desalination process and on the need of monitoring the amount of radioactivity that can be possibly released to the industrial process, the issues related to tritium are considered.

Control and operation strategies
The increased requirements for instrumentation and control (I&C) in a cogenerating plant are highlighted. As a further aspect of great interest, a full subsection is related to flexible operation. After suggesting the positive and negative features of load following, it is finally mentioned that:

> *"Operating a nuclear power plant in a cogeneration mode can easily relieve all of these constraints while offering a full and fast adjustment of the electrical output power of the plant. The primary circuit of the nuclear power plant may always work in a continuous mode at a full thermal core power, delivering at any time part of the nominal electrical power to the grid together with a cogeneration production using the remaining available heat. In that way, flexibility is ensured by deriving part of the thermal production to the cogenerated product — be it heat, steam, desalinated water, hydrogen or synthetic gas. No additional thermal or mechanical stress is expected from this operation on the nuclear fuel as compared with any standard baseload plant operation."* (ibid.)

This suggests a concept of substantial baseload mode production for the nuclear power plant to be considered as a useful alternative to load following. The present is an important potential option that we need to build a consensus on to derive our demonstration cases, also related to the various modes of polygeneration highlighted before.

Risk Assessment Considerations

After considering the specific situation of desalination plants, a more general perspective for risk assessment is proposed:

> *"In general, risk assessment for nuclear cogeneration encompasses three different areas […]:*
> *(1) Deterministic and probabilistic risk assessments to support licensing of advanced reactor technologies that interface with industrial process facilities;*
> *(2) Risks associated with development, deployment and commercialization of advanced reactor technologies;*
> *(3) Assessments associated with the industrial process facility that could impact safety of the nuclear cogeneration facility."* (ibid.)

The first two areas are partly related to the maturity of the innovative technology, requiring specific attention during the development of a new technology that cannot be completely considered proven unless on the basis of a sufficient industrial experience. For the third area, the following steps are considered:

> *"— Performance of a process hazards assessment of the industrial process facility;*
> *— Preliminary screening evaluation of event sequences associated with process hazards;*
> *— Detailed risk analysis of event sequences associated with process hazards and the impact of facility operations on the nuclear plant."*
> *"These elements should be included as part of the probabilistic risk assessment elements discussed above. […] the types of scenario that need to be considered in the definition of licensing basis events involving industrial process facilities include the following: […]"* (ibid.)

Here, a detailed list of possible accidents occurring in the process facility is reported, including fires, deflagrations and detonations, flammable vapour clouds, hazardous chemical releases, propagation of toxic materials from the process installation.

In summary, the chapter on safety issues of this report is worth to be considered to direct the work to be performed in the frame of TANDEM to set up an assessment methodology for discussing the safety margins of the nuclear reactors affected by the cogeneration coupling.

Industrial Applications of Nuclear Energy, IAEA (2017a)

This is another interesting report by the Agency, more focused on the general uses of nuclear energy in industry in different Countries of the world. The considerable potential of nuclear cogeneration is suggested providing the information that only 1% of nuclear power was at the time used for non-electric applications. In the perspective of continuity of industrial production, the issue of availability and reliability requirements of the NPP is addressed, suggesting it as a

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condition to be satisfied in nuclear cogeneration and as a clear positive feature of nuclear reactors, conceived for continuous production. However, it is stated that:

> *"The industrial requirement of full availability and reliability on energy supply needs additional backup systems, since any interruption of industrial processes can lead to disturbances, with potentially severe technical and financial consequences"*. Moreover: *"A final requirement is the need to ensure that under no circumstances can radioactive material find its way to industrial circuits and contaminate the end products delivered to the consumers. This will definitely have impacts on the nuclear design and the coupling system by defining a sufficient safety distance between the reactor and industrial applications."* (IAEA, 2017a)

Indeed, high temperature gas reactors (HTGRs) are the best suited for cogeneration. Instead:

> *"Cogeneration plants (both nuclear and fossil fuel) that operate under the low temperature conditions of existing water reactors derive their principal revenues from electricity. This poses challenges to the nuclear heat option […]*
> *(a) Two thirds of the nuclear energy produced in existing reactor types is heat, which is usually lost to the environment. To provide this heat at a high quality (higher temperatures and pressures), some of the electricity production needs to be sacrificed, further increasing the share of heat.*
> *(b) While the economy of scale principle is applicable to the generation of electricity, this does not hold for process heat, since heat cannot be as easily distributed as electricity."*
> (ibid.)

Concerning the safety aspects of integrated nuclear-chemical plants, it is suggested that:

> *"The principal requirement […] is that radioactivity is completely retained inside the plant even in extreme accidents, with no severe consequences outside the fence […]. Potential hazardous events in connection with the combined nuclear–industrial systems include the following […]:*
> *— Tritium transport from the core to the product hydrogen and methanol;*
> *— Thermal turbulence induced by problems in the chemical system;*
> *— Fire and explosion of flammable mixtures with process gases present in the system;*
> *— Release of toxic material.*
> *Operational and safety independence of the two systems are required to make the nuclear energy supply approach practical. Since the industrial application needs to remain a conventional plant for practical cost reasons, its performance should not undermine the operation stability and safety of the nuclear plant. Most importantly, […] - the production process system is not designed to take over safety functions for the nuclear system; these are exclusively left to the reactor cooling system. An abnormal loss of the heat sink on the*

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industrial side, for example, should not force the nuclear reactor to scram, but rather lead to an orderly transit to idle running conditions. Extensive simulation and practical experience with the thorium HTR have confirmed that the nuclear plant can quickly resume full power upon load recovery of the industrial plant […]. The overall safety concept for a nuclear plant coupled to an industrial facility consuming nuclear energy has to consider all conceivable mutual interactions given the proximity of the two plants. A first boundary, still part of the nuclear system, is the IHX, representing a barrier against primary coolant to transport radioactivity toward the industrial site. Impact on this component is principally given by temperature, pressure and corrosive attack. Rapid changes in these parameters including respective differences between primary and secondary side may be encountered under abnormal operating conditions on either side — resulting from loss of the heat source (nuclear reactor scram) or loss of the heat sink on the industrial side." (ibid)

The concept of safety distance and possible "barricades" is elaborated, considering the usual trade-off of keeping a prudent decoupling between the nuclear and the industrial unit and a feasible transport of the coupling means. Interestingly enough, it is considered that:

"There are other measures possible to minimize risk both on the nuclear and the industrial side, such as shutdown and disconnection systems or underground placement of the reactor building, positioning of the nuclear control room out of reach for any serious consequence of an industrial accident (e.g., blast wave and toxic vapor cloud dispersion), or minimization of the amounts of hazardous materials present on the industrial site […]"

In view of the need to locate the reactor close to urban areas and to the served industrial process, the location of plants conveniently underground may be considered as a useful alternative to its remote location.

Before devoting the rest of the report to describe the potential of various nuclear industrial applications, a paragraph is specifically devoted to SMRs:

"The simplest and most near term application with very large market potential for small sized modular nuclear reactors is the generation of high quality steam for consumers in the chemical and petroleum industries. Small units with the size of existing fossil fired cogeneration plants can take advantage of matching with the needs of the industries. In contrast, the large size of typical LWR units makes their thermal power levels too big to be consumed by any CHP application."

This highlights the relevance of the work being performed in the frame of TANDEM in this regard.

Proposal for a Technology-Neutral Safety Approach for New Reactor Designs (IAEA, 2007) and **Approach and Methodology for the Development of Regulatory Safety Requirements for the**

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Design of Advanced Nuclear Power Reactors Case Study on Small Modular Reactors (IAEA, 2022)

In preparation to the work to be done also in Task 4.2, IRSN suggested to consider these two IAEA reports (IAEA, 2007 and IAEA 2022) as particularly interesting for setting up the methodology for assessing safety margins for a LW-SMR in a hybrid cogeneration system. The two documents share the fact that they have been issued in periods in which the nuclear community was preparing for engagements in possible new builds considering innovative reactors; in this developing environment, the Agency confirmed principles to be implemented in this effort.

In particular, IAEA (2007) proposes a "technology neutral" approach to the safety assessment of new reactor designs, starting from the consideration that:

> *"The current design and licensing rules are applicable to mostly large water reactors and there are no accepted rules in place for design, safety assessment and licensing for new innovative nuclear power plants. This TECDOC proposes a (new) safety approach and a methodology to generate technology neutral (i.e. independent of reactor technology) safety requirements and a "safe design" for advanced and innovative reactors."* (IAEA, 2007)

The report is interesting for our purposes since it reaffirms principles already discussed in previous classical publications of IAEA (e.g., IAEA, 2000, shortly referred to in literature as NS-R-1, from its Nuclear Safety series coding, now superseded by SSR-2/1, i.e., IAEA 2016), in view of the development of a model for the development of safety requirements for new NPPs. The New Safety Approach is based on some pillars, being: (1) Quantitative Safety Goals (correlated with each level of Defence in Depth); (2) Fundamental Safety Functions; (3) Defence in Depth (Generalized) which includes probabilistic considerations). The use of a frequency vs. consequence curve bounding the regions of acceptable and unacceptable risk is mentioned as in usual probabilistic theories set up since the 60s and the 70s for nuclear reactor applications. The likelihood of occurrence of different events is discussed for the categories of AOOs, accidents (AC) and severe plant conditions (SPC). This approach is represented by a staircase curve of risk acceptance related to the different levels of defence in depth and to specific limit values of accident, in similarity with previous national methodologies for nuclear risk analysis (see Figure 5 in section 2.4.4.1 of the report). Apart from this and other similar details, the report, though not specifically suited for the purpose of assessing the safety margins of a LW-SMR in a hybrid cogenerating system, suggests a general methodology for expressing in a technology-neutral form the requirements of control of reactivity, removal of heat from the core and confinement of radioactive material, including the limitation of discharges in normal operations and after accidents.

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The very recent report by IAEA (2022) represents a Case Study specifically conceived for SMRs. The report *" is intended to help in the process of updating the regulatory guidance for licensing of advanced NPP designs, and particularly for SMRs, in States with an established system of nuclear regulations and guides. This publication identifies the typical areas for updating and proposes the basic steps for such updating. It can also be helpful to States embarking on nuclear power programmes in their preparation for development of their own legislation."* (IAEA 2022).

In particular, the report considers some selected design features of small modular reactors important for updating the regulatory design safety requirements on which specific considerations are proposed. They are listed as modularization, integral design, compact design, modularity, multiple barriers against releases of radioactive materials, passive design features and natural circulation, human factors, fuel enrichment and performance, safe reactor shutdown, coolant, coupled facilities, protection against internal and external hazards, confinement system, specific design features for ageing management, specific design features affecting radiation protection. For all these aspects, beside the advantages claimed by proposers of SMRs, critical issues are highlighted for which specific attention is recommended. For instance, some of these aspects may raise issues of accessibility of the different components for maintenance, or pose problems related the use of a technology that cannot be considered yet proven, owing to the lack of a sufficient operating experience. Passive features and natural circulation often suggested in SMR designs may give rise to weak driving forces or phenomena of "passive failure of passive systems" (e.g., owing to ageing or clogging). Moreover, in-service inspection may result more difficult in some design concepts and special considerations apply also for the human factor, e.g., for the sharing of the control room by multiple units. Though we are here highlighting the concerns, the report equally stresses the positive aspects of SMRs.

A mention more strictly related to the issues brought about by the inclusion of a small modular reactors in hybrid systems is made in relation to the item of "coupling". In this regard, it is stated that:

> "*Some SMR designs consider coupling with other facilities such as for hydrogen production, heat production or other chemical processes, for example metallurgy or mining of raw material (co-generation). Such combined use of SMRs offers an advantage since, in addition to economic benefits, it adds flexibility for stable utilization of full reactor power.*
>
> *On the other hand, coupling of an SMR with another facility adds complexity to the design due to potential interaction, both for ensuring smooth operation of the coupled facility as well as due to potential adverse interactions. Possible adverse impacts of the coupled facility on reactor modules need to be considered as external hazards, as potential initiators*

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of additional paths for radioactive releases and a possible source of security issues related to the need for accessing the coupled facility for operating purposes." (ibid.)

The issue of external events has therefore to be considered related to the issue of coupling, owing to the need to keep some proximity between the nuclear plant and the industrial process. In this respect, semi-buried or even underground locations are considered having positive and negative aspects, e.g., in relation to the possibility to decrease or increase the safety relevance of releases and also of natural events like flooding. In summary, no specific feature of an SMR can be considered completely positive or negative in the ends of safety and an accurate screening of the specific plant and site characteristics must be performed.

A detailed presentations of the steps to be completed to review and update existing safety requirements for SMRs is included in the report and can be used as guidance for the methodology to be proposed in the frame of TANDEM to assess the safety margins impacted by cogeneration. These steps are:

- "Step 0 – Determine the objective(s) of the review (background and pre-requisites);
- Step 1 – Examine existing requirement to understand the rationale and goals;
- Step 2 – Evaluate applicability of the requirement and identify gaps;
- Step 3 – Determine whether to adapt the requirement or develop a new requirement or guidance." (ibid.)

The reported considerations make most often reference to the levels of Defence in Depth (DiD) and to the concept of integrity of the multiple barriers, in a risk informed perspective. The use of an expert panel and/or of a Phenomena Identification and Ranking Table (PIRT) is also suggested to decide if a safety requirement is applicable to the specific plant conditions.

In summary, the report presents *"an updated methodology considering an integrated risk informed, objective oriented, performance based assessment approach that can be used for the development of regulatory safety requirements for the design of advanced NPP designs with different technologies, including SMR designs."* (ibid.) Owing to the recent date of issuance of this report (September 2022) and to the authoritative role of IAEA, the described rationale can be rightly considered among the reference ones to inspire the methodology to be set up in the frame of TANDEM.

Considerations for environmental impact assessment for small modular reactors, IAEA (2020a)

This document focuses on the main issues to be taken into account in performing an Environmental Impact Assessment (EIA) when Light-Water Small Modular Reactors are considered. The document is not focused specifically on cogeneration aspects, so it is mentioned only as one of the possibly several examples of application of safety principles in the design of advanced reactor concepts, namely of SMRs in this case. In principle, it is considered that *"The EIA process is expected to be similar for assessing potential environmental impacts for Large Rectors (LRs) and for SMRs."* (IAEA 2020a). The features and concerns that may differentiate the safety assessment (hence the EIA) of LRs from those of SMRs are listed. These features and concerns are not summarised here, since they are not specifically related to cogeneration aspects.

For cogeneration, it is pointed out the fact that a coupling between a Nuclear Power Plant and an Industrial Process may bring to events which are not considered in a normal safety assessment for larger reactors. In fact, the following is stated: *"Cogeneration and co-location with other facilities – Should an accident occur at an SMR, a collocated industrial facility could be affected and stressors to the environment may be released from both the SMR and the other facility. There also exists the possibility of an accident occurring at the other facility that in turn affects the associated SMR, with a similar effect of releasing stressors from either one or both facilities."* (ibid.)

Admittedly, the conclusions of this document must be taken with due care, owing to the incomplete maturity of the sector of SMRs; in fact, it is stated that *"[…] many of the SMR designs in various Member States are still at a conceptual level. In other words, an SMR is conceptually defined, but it still has to be approved by appropriate national authorities, built and operated. Accordingly, the benefits claimed by SMR manufacturers, such as fabrication of modules offsite and assembling of the modules at the site where the SMR will operate, still have to materialize. The experiences during regulatory approval, construction and operation of SMRs may also result in changes to the SMR designs."* (ibid.). Therefore, any conclusion in this regard must be taken as work in progress.

Applicability of design safety requirements to small modular reactor technologies intended for near term deployment, IAEA (2020b)

In this document, the applicability to SMRs of the Specific Standard Safety Requirements by IAEA indicated in the document Safety of Nuclear Power Plants: Design (S.S.R. No. SSR-2/1 (Rev. 1)) is assessed. Both LW and HTG SMRs are considered. Concerning Light-Water SMRs, few considerations/modifications are suggested about the already fixed Standard Safety Requirements, mainly concerning the possible multi-unit configuration of LW-SMRs. It is suggested that an external hazard impacting one unit, which might be brought about by the thermal coupling with an industrial process, may cause issues on other units of the plant. It is worth mentioning the full paragraph introduced in regard:

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> *"SMRs are normally designed with the flexibility to allow coupling to a heat utilization facility instead of, or in addition to electricity generation, to a greater extent than traditional large NPPs. In this case, the heat utilization facility may be located off the licensed site of the NPP, and as such the treatment of hazards and transients initiated by the heat utilization facility will require careful consideration during the design development of the SMR. Therefore, enhancements in the wording of the safety requirements related to coupled facilities may be needed to ensure that these aspects are adequately addressed."* (IAEA 2020b)

Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operation, IAEA (2018)

Load following is here considered for potential risks, effects and possible countermeasures. The report is quite extended and it is not possible to summarize here all the aspects considered, which are anyway common to all reactors in load following operation. Since the reactor is not working at full power for long periods, the question is raised whether safety analyses should be repeated also for conditions starting when the reactor is working at partial load, whenever they were not addressed since the beginning in the safety analysis reports. In fact, *"a presumption of baseload operation may exist in the plant licensing basis, and this would affect the scope of the safety analysis report. For example, the licensing basis of a plant may limit the safety analysis of AOOs and DBAs only to reactor startup conditions (subcritical up to hot zero power) and full power conditions."* (IAEA 2018). This may be not the case for SMRs conceived for cogeneration since the very beginning; therefore, these issues are here mentioned just to suggest the more general frame in which the possible load following strategies of SMRs must be considered and also to warn about the way in which safety assessment should be performed for an SMR conceived for load following. Additional concerns regard thermal load and fatigue, potential fuel/cladding interactions due to thermal expansion cycles, additional wear and tear of components (valves, pumps, etc.), core power redistribution, additional corrosion/erosion, length of the operating cycle and ageing. At page 47, the report includes an interesting table of *"aggravated phenomena by flexible operation and affected plant systems, structures and components"* which represents an interesting summary of the related concerns. In the Conclusions, before detailing the aspects raised by flexible operation, it is stated that:

> *"Baseload operation of nuclear power plants is the preferred mode of operation, because it is the most efficient use of capital invested in plants as well as being simpler than other modes. For these reasons, the majority of plants are currently operated as baseload generating units. However, there is a recent and increasing need in some Member States for plants to be capable of operating flexibly for a variety of reasons. As grid flexibility becomes necessary and inevitable, with an emphasis on reducing global greenhouse gas emissions and increasing the use of renewable energy and the share of nuclear generation, electricity grids would benefit from increased flexibility."* (Ibid.)

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The list of issues and suggestions reported in the Conclusions is therefore precious for dealing with specific aspects of SMRs conceived to be flexible enough in an energy mix including intermittent renewable sources and must be attentively considered for the multitude of technical aspects considered. As it will be mentioned below, the use of storage, whenever possible in the future at the required level of capacity, might therefore mitigate the requirements of flexibility to be applied to nuclear production, bringing it as far as possible towards the standard mode of utilisation for stable and safe baseload production.

A Literature Review: Smart Grids Impacts on Nuclear Power Plants, BNL report by Villaran (2016)

This report represents a quite interesting piece of information on safety aspects of the interconnection of nuclear reactors with electrical grids dominated by intermittent renewable energy sources, though it is not necessarily targeted to SMRs and is mainly referring to the USA scenarios. The discussion is mainly inspired by the General Design Criterion 17, in Appendix A to 10 CFR Part 50, related to the need to supply electricity to the NPP in a reliable and stable way: this is considered as one of the main problems in an electrical grid including intermittent sources, where the quality of the off-site power provided to NPP may not be sufficient for nuclear standards. A specific USA issue is the one of the multiple transmission system operators, causing a lower reliability of the electrical supply; how much this concern may apply to Europe needs to be established.

The report features also an attentive analysis of Smart Grid impacts in the presence of solar and wind sources. A specific concern about the lower electrical grid inertia, brought about by the presence of inverters in place of large rotating machines, is discussed in relation to the mentioned aspect of the quality of electricity to be supplied as off-site power to the nuclear plant in case of need. Microgrids are also considered and the vulnerabilities of smart grids (due to distributed sources, system storage, microgrid characteristics, sensing-measurement-control, etc.) are discussed.

The impact of an increasing share of intermittent renewable sources on the quality of the electricity is also considered; in particular, the "duck plot" in Figure 1 is discussed to show that the *"net load seen by the grid over a day, which is the difference between the forecasted load and the renewable generation available, will decrease at mid-day due to over-generation of renewable energy".* This source of intermittency is mainly due to the daily cycle of solar energy. It is mentioned that *"There are ways to mitigate this variability, including the use of geographic diversity of plant locations and energy storage systems […], but there are limitations on the degree to which these solutions can be implemented. Locating renewable generating plants is subject to the availability of suitable land with an acceptable energy resource. The use of energy*

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storage systems is currently very expensive and may be difficult to justify economically." (Villaran, 2016). Transmission reliability standards are also given attention for the differences between the nuclear and non-nuclear regulations. Grid risk sensitive activities are considered, e.g., potentially leading to trips, loss of off-site power (LOOP), station black-out (SBO), etc. Moreover, the impacts of smart grid dynamics on nuclear safety and the possible cybersecurity issues in such grids are considered.

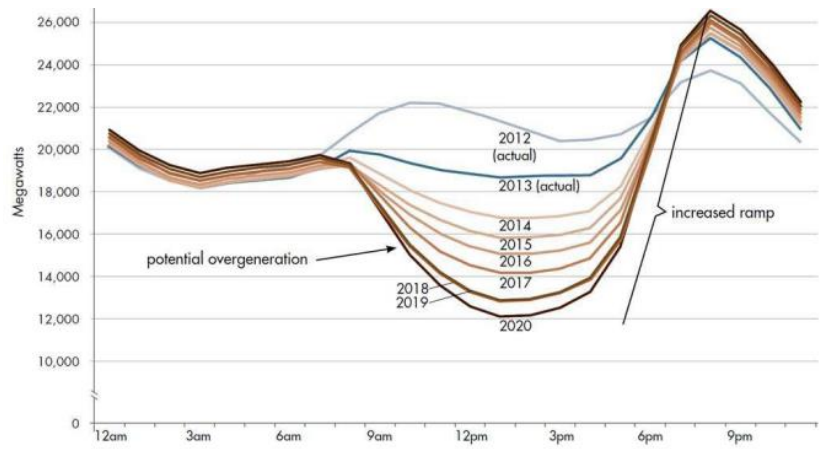

Figure 1: The "duck plot" (adapted from Fig. 3.4 in Villaran, 2016)

Technical and Economic Aspects of Load Following with Nuclear Power Plants, OECD/NEA (2011)

Again on the subject of load following capabilities, this NEA (2011) report summarises the issues and the experience related to the use of nuclear reactors for flexible energy production. The experience in France is firstly taken as reference and the manoeuvring capabilities of nuclear reactors are considered. Technical and economical considerations of the operation in load following are then addressed. In relation to manoeuvring capabilities, a table at page 20 of the document summarises the relevant characteristics of French PWR-900, PWR-1300, and N4 reactors. Documents of the Electric Power Research Institute (EPRI) in the United States and the European Utilities' Requirements (EUR) in Europe are considered for limitations applied to manoeuvring. Among the different considered aspects, the load following capabilities of existing power plants in terms of possible power ramps are considered also depending on the stage in the fuel cycle (at BOL or EOL). Moreover, the influence of load following on the life-time expectancy of large components is discussed with (a few) recommendations for number and kind of power cycles that can be safely tolerated by the plant. Indeed, in terms of fuel performance, the manoeuvrability of the reactor could be limited by cladding failure due to the pellet-cladding

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interaction (PCI), stress corrosion cracking (SCC) and other effects on which there is knowledge coming from present applications. These aspects will need to be critically considered in the frame of TANDEM for SMRs in cogeneration conditions.

Further miscellaneous sources

Two papers in the available literature, Denholm et al. (2012) and Ross and Bindra (2021), tackle the issue of energy storage for a nuclear-renewable energy mix. The two papers, selected among a broader set of works on the subject, suggest adopting energy storage to avoid decreasing the economic convenience and the safety level of nuclear reactors by using a too high degree of flexibility.

In particular, Denholm et al. (2012) suggest that meeting load variations has significant economic impacts: 1) increase of maintenance requirements and decrease of operational life; 2) reduction of capacity factors and increase of electricity costs; hence, as well known, load following is feasible but costly. Thermal Energy Storage (TES) may be considered since *"[it] represents an alternative pathway that offers potential advantages over many existing electricity storage technologies. Since thermal storage stores energy before the losses associated with conversion to electricity, it can feature round-trip efficiencies that exceed 95%"* (Denholm et al., 2012). In the scenario considered in the work "*renewables are assumed to contribute 60% of annual demand (after a small amount of curtailment) and the relative contributions of wind, PV and CSP are 60%, 20% and 20% respectively."* (ibid.) Preserving the nuclear reactor from additional transients due to interfacing it with renewable sources is one of the targets: *"We assume that the nuclear power plant produces thermal energy at a constant output, and this thermal energy can either be diverted into the power block or into storage."* (ibid.) This is similar to the assumptions already mentioned for the paper by Locatelli et al. (2018) mainly using alkaline electrolysis. *"Coupling a nuclear reactor heat source to a thermal energy storage system is not difficult from a conceptual sense, but the design space is large, and a number of different reactor designs and thermal energy storage methods are possible."* (ibid.) Among the different challenges: 1) at the level of design, to couple the NPP with the storage; 2) at the level of safety, to understand coupling implications; 3) at regulatory level, owing to the uncertainties in the licensing process. It is interesting to note that a mentioned possible advantage is the availability of a power block capable to absorb a full day of production, that could possibly absorb one month or more of decay heat, being a source of cooling power as a possible remedy to Station Blackout conditions. A few excerpts from the conclusions, summarise the main message of the paper:

> *"A grid employing large amounts of wind and solar energy requires the balance of the system to be highly flexible to respond to the increased variability of the net load."* (ibid.)

> *"One possible solution is to couple thermal energy storage to nuclear power plants. This would enable the reactor to remain at nearly constant output, while cycling the electrical generator in response to the variability of the net load."* (ibid.)

Ross and Bindra (2021), in a much more recent analysis, start from the assertion that *"It is unsafe to make use of a NPP in load following mode and, anyway, it introduces a bad economical influence; so storage is necessary, mainly trying to keep the NPP within its "safe limits""*.

An explicit reference is made to the EUR requirements (something that is of specific interest for the TANDEM Project) in relation to the safe limits of load following. This aspect should be deepened, to understand the present prescriptions for a safe conduct of NPPs in load following, trying to critically discuss their applicability to the novel technical characteristics envisaged for SMRs. The use of storage is not very clearly defined in the paper, with mention of a few techniques likely to be used. However, storage is suggested as necessary in the opinion of the authors for an acceptable management of a hybrid nuclear-RES system.

The mention to European Utility Requirements is made suggesting that: *"These EUR guidelines dictate the load-following limitations for reactors for both small and large power changes in normal and emergency operating modes over the lifetime of the fuel. For a maximum rated reactor power, P_0, the reactor can cycle between 2%P_0 and 5%P_0 at a rate of 1%P_0/s with no impact on the reactor fuel. Changing the power by ±10%P_0 of the rated power at a rate of ±5%P_0/s should also have no effect on the fuel over its lifetime. The reactor power should be able to change by ±20%P_0 at a rate of 10%P_0/min for 20,000 cycles over the lifetime of the fuel. The reactor, under planned operating conditions, should be able to withstand power increases or decreases in the range 50%P_0 to 100%P_0 at a rate of 5%P_0/min for up to 20,000 cycles safely. Under emergency conditions in the same regime, the ramp rate can increase to 20%P_0 while the power is decreasing."* (ibid.) As said, how much these prescriptions may be applicable to SMRs in cogeneration will depend on the characteristics of the SMR plants and on the needs for interfacing them with RES and industrial processes. The paper develops case studies to support the conclusion that the adopted model, based on a stochastic treatment of renewable energy source (RES) intermittency data, can be used to optimize the control management strategy.

Samul et al. (2013) present a general discussion on SMRs and their advantages/disadvantages. There are relatively few specific considerations on safety issues.

Murakami et Anbumozhi (2021) present a literature survey on SMRs and a summary of their adoption in the international context is presented in this research project report; mention of use of hybrid systems and of load following capabilities is found in the publication, together with an expert opinion on SMRs.

The paper by Locatelli et al. (2018) presents a techno-economic feasibility study of nuclear power plant load following by cogenerating hydrogen (by Alkaline Water Electrolysis, AWE, High Temperature Steam Electrolysis, HTSE and Sulfur Iodine thermochemical processes, SI). No specific safety issue is addressed; however, the paper starts from the assumption that operating the nuclear reactor in load following is inefficient at least from the economical point of view and that a more attractive option is to maintain the primary circuit at full power and to use the excess power for cogeneration. This point of view is quite relevant in this context and has also implications on safety: as repeated by many sources, stressing the reactor by continuous cycling, in order to follow the load in an energy mix dominated by variable renewable sources, may result not only inefficient but also unsafe.

Integrated Energy System (IES) Program

A further source of information is the Integrated Energy System (IES) Program supported by the U.S. Department of Energy's Office of Nuclear Energy, carried out by national laboratories and in particular by the Idaho National Laboratory (INL). This program (see the IES website) has a very comprehensive structure, providing information about several aspects of interest for the TANDEM Project, including a discussion of the issue of flexibility of nuclear power in cogeneration applications. Owing to time limitations in the present step of the analysis, the material being produced in the frame of this project was considered only in general terms. It is anyway recommended that the project will keep a tight connection with the ongoing R&D actions at INL, in order to exploit useful synergies in view of new developments.

2.3 Summary of relevant issues emerging from the survey

In consideration of the scarcity of information directly pertaining to LW-SMRs in cogeneration applications, it is necessary to draw from the above presented panorama specific suggestions for the work to be carried out in the frame of TANDEM, in the purpose to adapt concepts mainly referring to other reactors (e.g., HTRs and FRs) to the cases in consideration.

A list of the subjects highlighted by the previously reported material is provided hereafter in this purpose, aiming to suggest the main topics to be covered by the work of setting up the assessment methodology targeted by the TANDEM project.

- Definition of the cogeneration application and of the energy mix scenario

Many of the aspects to be clarified in relation to the safety assessment depend on the interaction between the nuclear SMR and the electrical grid in which it is included, in addition to the industrial process that it is intended to serve in a cogeneration perspective. In relation to the latter, in the TANDEM project the situation is clearly specified since the very beginning, as detailed in the Grant Agreement:

> *"TANDEM intends to focus on two main study cases corresponding to hybrid system configurations covering the main trends of the European energy policy and market evolution:* ***a district heating network and power supply in an urban area, and an energy hub serving energy conversion systems, including hydrogen production, in a regional perspective****."*

Concerning the degree of penetration of renewable energy sources in the electrical grid, which represents an additional aspect of context for studying the safety of the cogenerating SMR, assumptions have instead to be made. These aspects are the subject of developments in the frame of TANDEM, as the specific target of deliverable D1.1 (Goicea, 2023), whose conclusions will have to be considered in setting up the safety methodology. Moreover, WP3 will provide results about techno-economics, environmental impact and operationality of hybrid energy systems integrating LW-SMRs. The results of these studies within TANDEM will include information about the flexibility to be requested to SMRs.

Indeed, something to be stressed with no ambiguity is that, if load-following or flexibility to cope with a cogenerating process are asked to an SMR, its safety analysis will change substantially at the level of assumed initial conditions for the deterministic evaluation of accidents: in fact, it will be necessary to include a full range of starting conditions with partial load operation, thus making more varied and complex the analysis.

- Degree of decoupling of the NPP from the grid and the cogeneration process

Though cogeneration will necessarily imply coupling with the industrial process (for TANDEM, namely district heating and hydrogen production), the issue several times encountered in previously considered references is the one of the degree of decoupling from the process as well as from the electrical grid. The following aspects need to be considered:

- <u>differences in regulations</u> applicable to the industrial process and to the nuclear power plants: in some of the references, it was suggested that the two environments should not be mixed from a regulatory point of view, though the related interfaces should be adequately managed;
- <u>differences in standards:</u> e.g., this applies to cybersecurity issues, which may be treated with different relevance in a nuclear and non-nuclear environment, but also to hardware requirements (e.g., codes of regulations applied to component design);
- <u>physical separation</u>: a sufficient distance of the NPP from the production process seems to be necessary though, depending on the degree of inherent safety of the SMR, this distance could be reduced with respect to the case of large reactors, assuming a low Large Early Release Frequency (LERF), if this will be proven; however, since the industrial process is also an "external" initiator of possible nuclear incidents

and accidents, the appropriate separation between the NPP and the industrial user must be attentively discussed also based on industrial risks;

- ownership separation: it can be assumed that the ownership of the NPP and the one of the district heating grid or the hydrogen production plant may be different;
- human resource separation: it seems necessary to evaluate if the workers of the NPP and the ones of the industrial application have to be subjected or not to the same regimes in terms of radiation protection and protection from other hazards, a frequent opinion being that it should not be the case;
- bidirectional barriers: it seems necessary to avoid mutual negative influence on the safety of either installation, using appropriate separation barriers, active in both directions.
- Level of nuclear safety and interfaced industrial application

A principle repeated several times in the considered references is that the level of safety of the nuclear power plant should not be adversely affected by the presence of the interfaced industrial application. This issue is definitely linked to that of the separation and of the interposed barriers. Indeed, the safety assessment methodology seems to have necessarily to consider the combination of the two systems and to assess the safety of each one of them and of their combination in a cogenerating environment. Important aspects, e.g., as the definition of the extent at which maintenance of the nuclear power plant can be conditioned to the needs of the cogenerating application, must be considered.

- Methodology of safety analysis

It must be clarified if the usual methodologies of probabilistic and deterministic safety analysis can be considered sufficient for the cogenerating system, once integrated with an appropriate evaluation of the "external" risks induced by the interfaced industrial application. In particular, it must be considered if the usual concepts of Defence in Depth (DiD), Multiple Barriers and other similar concepts proposed, e.g., in IAEA reports, in the European Utility Requirements and in national regulations can be safely applied to the present case, once the appropriate ingredients in terms of external risks coming from the interfacing industrial application have been included. Questions as the one of the applicability of the principle of designing against the single-failure to the combined nuclear and cogenerating plants need to be assessed.

- Flexibility in NPP operation

Issues as the degree of load-following and the flexibility of the NPP in view of the needs of the cogenerating application must be considered, as already mentioned above. At a higher level, it must be decided if the nuclear plant should be operated in load-following to accomplish with the needs of the industrial application and of the electrical grid or if an attempt should be made to keep the NPP operating at a constant regime, with a dynamic partitioning of the power between electricity production and district heating or hydrogen production or heat storage. Indeed, this choice will condition the type and the frequency of anticipated operational occurrences to be considered in the safety analysis of the plant. As several times mentioned above, economics and safety are strongly affected by this choice; on the side of economic considerations, given the need to show competitiveness of SMRs while fighting against the intrinsic disadvantage of the loss of the economy of scale, would suggest opting mostly for a continuous full power operation of the plant.

- Safety of the electrical energy supply to the NPP

As pointed out in the BNL report by Villaran (2016), the introduction of a nuclear power plant in an electrical grid dominated by Renewable Energy Sources will pose the problem of the availability of a sufficient quality of the off-site electrical power to be provided to the plant in case of need. This has again to do with the frequency of the AOOs to be assumed in the safety analysis of the nuclear power plant. In this regard, energy storage and an architecture that can make the nuclear reactor sufficiently autonomous from the electrical grid (e.g., making use of internal turbo-generators or sufficiently reliable and effective passive engineered safety features) may strongly improve the safety level achieved in the cogenerating hybrid system.

- Impact of the NPP on the industrial process

At the risk of repeating some of the above mentioned issues, it is necessary to single out the importance that aspects of the possible radioactive contamination of the heat carrier may have of the linked industrial process. Likewise, the requirements of stability of the production of the exchanged heat must be assessed.

- General safety issues of SMRs in view of licensing

SMRs have peculiarities that have a role in the coupling of a nuclear installation with a cogenerating plant as well as for the general licensing process. Safety concerns are related to the modularity and multi-unit characteristics (e.g., due to the interaction between modules in terms of common mode failures, characterisation of the source term from multiple units on a site, etc.). An issue to be clarified is the one of the "graded" approach, in relation of the claims of higher safety of SMRs with respect to large nuclear reactors and to the nature of "advanced" (i.e., not yet "proven" or even FOAK) nature of their concepts.

- Definition of meaningful study cases

Considering the applications to be analysed in TANDEM, suitable case studies should be identified, in order to exercise the safety assessment methodology on the basis of meaningful conditions. Identification of existing installations that can be considered as a basis for case study development may help in regard.

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3 Best practices for safety assessment of flexibility and cogeneration

3.1 Considerations by GRS

Large scale LWR nuclear power plants in Germany were designed when projected in the 1960ies and 1970ies for sufficient flexibility of operation. This led to dedicated requirements for safety of related to operational transients over the life-time both in terms of total number, variation of power levels and change of power levels. And in one power plant in Germany (Kernkraftwerk Stade), co-generation was implemented since 1981 to its permanent shutdown in 2003 by providing process steam to the salt works next to the power station. The Stade plant was licensed based on applicable German regulation at the time and complied with the evolving regulatory expectations throughout its lifetime. Another case with some relevance is Kernkraftwerk Lingen, operating from 1968 to 1979. This plant was equipped with an oil-fired superheater in the secondary circuit. The hazards associated with such a feature have some similarity to hazards from co-generation approaches. Finally, Kernkraftwerk Krümmel was located in an industrial area and connected to a gas turbine for alternative emergency power supply that was located outside the actual plant perimeter.

Furthermore, cogeneration was a feature of smaller gas cooled (high temperature) reactor concepts developed in Germany e.g. at Kernforschungszentrum Jülich. Both aspects were considered at GRS with respect to safety assessment as well as with respect to meeting regulatory safety requirements.

3.1.1 Flexibility of normal reactor operation

For flexible reactor operation including load-following, thermo-mechanical consequences are an important area to be addressed in safety assessment.

Pressurized components of nuclear power plants are designed in accordance with applicable design criteria as well as codes and standards. This ensures

- the integrity of the pressure-retaining walls and structures
- the structural safety of the components and
- the functional capability of the active or passive components

for the intended lifetime. To ensure the functionality of active and passive components, the mechanics of movable parts as well as the deformation behaviour of the components under load must be considered separately.

Basic data for the design of the components come from the design specification. First of all, all possible load cases for normal operation and for load cases that deviate from normal operation, e.g., malfunctions are considered in terms of load. This is also done for the load-follow operation of the plants. Both types of load-follow operation (primary or secondary control) are assigned to normal operation. Here, the control modes are with relation to the transmission grid, see below.

The load cycles assigned to the load cases are described in a load spectrum, which, in addition to start-up and shut-down processes, include load cycles of ongoing operation. Furthermore, cycles for load cases that deviate from normal operation are also recorded. This also includes postulated malfunctions. Load cycles cause stresses in the components as a result of temperature and/or pressure changes that occur. The load spectrum determined in this way is then the basis for determining the lifetime of the components, for which an analysis of the mechanical behaviour if these components is necessary. For safety assessments, the core (fuel rods), primary circuit components as well as secondary circuit components need to be investigated. However, other components, e.g., in safety provisions, might be affected as well and thus need to be considered.

The frequency of the load cycles is set to a high level that would cover a number of regular load-follow operation events during the intended lifetime of the power plant. The data of the planned operation are specified by the plant operator. For load-follow operation, both step and ramp load cycles are specified. Both types of load cycles can occur in different power ranges.

The load-follow operation is a design requirement and differs for each plant and type of LWR. For PWR an immediate load following is set to 10 % of maximum power each 5 minutes in the range of 20 % to 100 % of the maximum power. For BWR a ramp type load following is considered of 30 % per minute in the range of 70 % to 100 % of the maximum power.

Furthermore, the speed of the load following is depending on the kind of control: local/primary control forced by the operator and distance/secondary control by the grid operator/load dispatcher.

In the load-follow operation, different systems are affected in the primary (and secondary) circuit depending on the type of LWR for which the above-mentioned criteria need to be assured.

Overall, load-follow operation imposes increased loads on the affected systems and their components. The effects of these loads on the system, the active components contained therein, e.g. pumps, valves, filters and control rods, as well as its availability are plant specific and need to be investigated for each plant.

Details of this generic approach can be found in Reck et al. (1990).

In 2020, GRS analysed the load following operation and other conditions and power gradients forced by the grid for the still operating LWR in Germany (Arians et al., 2020). Additionally, load-follow operation approaches in other countries are described, which are applied by different operators. For the German plants it was concluded that currently several power gradients are foreseen for operational conditions for different kind of load management aims. These aims could also be combined, which could make a safety assessment for the above-mentioned criteria more complex. Because each licensee is responsible for the safety assessment of its plant, a set of flexible conditions can be considered, but a general statement is not possible. Flexible operation might require an adaption of instrumentation and control systems to facilitate and safety execute the required load changes. Going beyond to Reck et al. (1990), the consequences of load-follow operation on systems and components were investigated more specifically, focussing on the evaluation of flexible operation impact on plant safety. With regard to fatigue-relevant loads, it can be stated that flexible operation was taken into account in the design of German nuclear power plants and that the specified number of load cases is not expected to be exceeded. Regarding corrosive loads, deviations from the specified values of the water chemistry, which can lead to corrosion, will be noticed at an early stage due to the water chemistry control. The risk of an unmitigated accident due to these corrosion mechanisms can thus be considered to be practically excluded. Active mechanical components are subject to increased stress as a result of flexible operation. This can lead to an increased failure rate for these components, and such failures could trigger initiating events for the reactor.

3.1.2 Safety aspects for the coupling of SMR with chemical processes (for GCR and MSR)

In Buchholz et al. (2015), several SMR concepts are described and the safety requirements for cogeneration are summarized for gas-cooled and molten salt reactors in Appendix B. A large part of these considerations and requirements can be transferred to cogeneration applications in light water and liquid metal reactors.

Some SMR concepts aim to supply remote settlements with electricity, district heating and drinking water produced, e.g., from lake water. A significant share of the energy consumption in developed industrial countries is used for process heat in industry and district heating. In the low-temperature range, where light and heavy water reactors are located, there is already experience, for example with the extraction of process steam for the paper industry or salt works.

With reactors cooled by gas or molten salt, electricity and process heat can be generated from nuclear energy in the temperature range from 550 °C to approx. 1,000 °C with high degrees of efficiency. The coupled use of electricity and process heat increases the utilisation of nuclear fuel

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on the one hand and could save large quantities of fossil fuels on the other hand, as long as process heat cannot be produced from renewable sources.

For this usage, nuclear heat generation systems should be coupled with chemical or thermochemical plants preferably over relatively short distances via heat transport networks in order to minimize losses and maintain efficiency. The specific risk potential in each case must be considered in the design of the facility. Consequently, care must be taken to ensure that incidents or even accidents in one part of the plant do not spread to the other coupled parts of the plants and thus initiate fault sequences with serious on- or off-site consequences. It is equally important to decouple the operational material flows to prevent chemically problematic substances or radioactive nuclides from being transferred from one material cycle to the other. When considering safety, a distinction must be made between hazards that result directly from the coupling of the different parts of a plant and those that affect the plants via processes external to the plant.

3.1.2.1 Fundamental considerations on the safety of coupled nuclear and chemical facilities

When the coupling of nuclear process heat generators and chemical or thermochemical processes is discussed, the focus is usually on the generation of hydrogen as a future energy carrier or chemical feedstock. But other chemical processes, such as ammonia synthesis, are also candidates for the use of nuclear process heat. Current plants produce 1,000 t to 1,500 t of ammonia per day, with a demand for process heat of about 300 MW to 450 MW at a temperature level of 500 °C to 1,000 °C. The production of 1 t of ammonia causes the formation of about 1.2 t of CO_2. For the use of nuclear-generated process heat, temperature levels in the range of 500 °C to 1,000 °C are considered in the following. The main focus of the following explanations is on the coupling of gas-cooled (GCR) and molten salt-cooled (MSR) SMR concepts with chemical plants.

When providing nuclear process heat on an industrial scale, it is important to ensure that there is no 1:1 allocation of nuclear heat generation systems to a single chemical production plant. This would have the consequence that all fluctuations in the heat demand would have an almost unfiltered effect back on the reactor plant, which could lead to abrupt load changes in the event of operational disturbances. In this case, the heat load would have to follow a potentially highly fluctuating operation of the chemical plant, which would require undesired cyclical control processes with the risk of instabilities on the part of the nuclear plant. Diversification on both the customer and supply side of the process heat supply is suitable for dampening fluctuations and maintaining the required narrow margins of power and temperature level. Therefore, only matched power classes of chemical industries and reactors should be assigned to each other,

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which can then also provide the necessary reserve power for safe operation of the consumer side.

The plants for nuclear heat generation are to be designed for combined heat and power. With a balanced design of the entire system for process heat generation, only a part of the power generated in the reactor is ever made available for the chemical processes. The remaining part can then be used for electricity production. This means that the consumers of the process heat can also be supplied with the electrical energy needed to operate the systems. In addition, the surplus electricity produced can be fed into the public grid. In the event of extraordinary peaks in demand for process heat or partial failure of the heat supply, electricity production can be reduced in favour of heat supply. Any bottlenecks on the power supply side can be bridged by drawing electricity from the public grid. However, the aim should be to decouple the reactor concepts used for energy supply from external power fluctuations as far as possible and to maintain nominal load operation that is as undisturbed as possible.

3.1.2.2 Safety requirements for the coupling

The equipment for heat transport from the nuclear heat source to the chemical process represents the actual coupling of the plants. These components - pipelines, fittings, heat exchangers and also the heat transport media - must be optimised in the overall concept for the operational requirements and possible incidents. For that the following aspects must be considered:

- Possible radiological hazards from the physical coupling of nuclear and chemo-technical facilities
- Possible chemical hazards due to the physical coupling of nuclear and chemo-technical installations
- Possible energetic hazards due to the physical coupling of nuclear and chemo-technical facilities

3.1.2.3 Safety against external impacts from coupled nuclear and chemo-technical installations

Nuclear and chemical plants each have specific accident-related hazard potentials for their immediate surroundings. The spatial proximity of such facilities increases this hazard potential. Consequently, precautionary measures must be taken against possible damage propagation. Requirements in this regard are formulated in general for nuclear power plants, which are to be suitably expanded due to the close coupling of nuclear and chemical or thermo-chemical process plants. Therefore, the following aspects must be considered:

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Additional hazards due to the coupling of chemical installations with nuclear facilities

- Potential of radiological danger
- Potential of chemical danger
- Danger of fire
- Danger of explosions
- Danger of missiles generated by pressure part failure, explosions or deflagrations
- Danger of toxic substances

It should be noted that these types of hazards are already within the scope of man-made hazards and internal hazards covered by existing regulatory guidance. Consequently, there is relevant good practice on the assessment of such hazards in a safety case for a nuclear facility. This needs to be transferred to the specific situation for a co-generating plant.

Potential safety measures

The protective measures to be taken must always be oriented towards the respective local conditions. General quantitative specifications are hard to determine. Nevertheless, general criteria must be observed, on the basis of which the planned safety measures can be assessed. In principle, nuclear and process plants can be protected from possible mutual interference effects by maintaining large safety distances. However, this is in direct contradiction to the demand for the shortest possible transport distances for the nuclear-generated process heat. Thus, an overall solution consisting of the geometric arrangement of the plants in relation to each other and the engineering design of protective measures to fulfil the safety-related criteria must be developed.

The release and distribution of toxic or flammable substances from chemical plants or storage sites can pose considerable risks to the safety of neighbouring nuclear plants and other plants belonging to the energy network. The accumulation of reactive substances in ventilation systems or cooling systems with natural convection can lead to flammable or even explosive environments. Appropriate sensor systems can be used for the timely detection of hazardous substances used in neighbouring process plants. When these are triggered, measures such as building and ventilation isolation would then have to be initiated. However, the accessibility and operability of safety-related plant areas and control equipment must always be guaranteed.

Special attention must be paid to the assumed effects of aircraft crashes on the connected chemo-technical plants. In addition to the effects due to explosion and fire of the aircraft fuel, problematic combustion products from the chemical reactions of the burning fuel with starting materials and end or intermediate products in the affected chemical plants must be expected. These combustion products are formed in an uncontrolled chemical environment with unclear

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conditions regarding the species and concentration distribution of the reactants. In such cases, the secondary products are difficult to predict. In particular, they may have toxic or corrosive properties from which the operating teams and safety-sensitive equipment of the nuclear and neighbouring chemical plants must be protected. Since it cannot be ruled out that previously unknown substances are formed under these conditions, a complete detection of the pollutants cannot be comprehensively ensured by pre-installed sensors.

If the co-generation plant produces hazardous materials, like hydrogen or other flammable, explosive or corrosive substances, transport provisions for these products similarly merit a dedicated assessment. Pipelines might leak, leading to flammable and/or asphyxiating gas clouds affecting the safety of the nuclear facility. Transport with heavy goods vehicles, e.g., and the associated movement on site will generate a specific hazard profile.

General safety criteria can be derived and quantified from the requirements for the safety of nuclear power plants and specific regulations tailored to the special characteristics of the associated chemical plants. Finally, compliance with these criteria has to be demonstrated in licensing and supervisory procedures by means of safety analyses that include the overall arrangement of nuclear and chemo-technical facilities. Not only technical aspects have to be taken into account. Ultimately, administrative issues, up to and including responsibility for licensing and supervision, must also be determined.

3.1.2.4 Control of the energy grid

Of great importance for the safety of the coupled industrial complexes consisting of chemo-technical process plants and GCR and MSR is a consistent control of the energy flows that adapts to the needs of the heat consumers, which should therefore be carried out centrally. This control essentially has three degrees of freedom. These are:

- Supply of process heat according to demand
- Supply of the required electrical energy
- Flexible balancing of power plant capacities and process heat demand by purchasing electricity from or feeding it into the public grid.

Chemical processes are only partly operated as continuous processes with continuous material flows and almost constant process heat demand. The majority of industrial processes, on the other hand, are carried out in "batch mode". This means that a reactor is loaded with the required starting materials. The chemical reaction then takes place in the closed reactor under the application of a certain pressure and the supply of heat until a state of equilibrium is reached between the starting materials and the end products. Continuous and batch processes have in common that the success and safety of the running processes depend, among other things, on the reliable supply of process heat within narrow power and temperature limits.

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In the past, nuclear reactors have shown that they can flexibly adapt to fluctuating power requirements, even with high load change speeds. However, this is associated with considerable thermal loads, especially on the fuel. In the case of frequent cyclical load changes, it must therefore be examined whether the fuel's ability to retain fission products could be affected. In general, for safety reasons, large thermal plants should be operated as uniformly as possible in the range of the design point. For GCR and MSR with combined heat and power, this means that the thermal reactor output should be kept as constant as possible and varied flexibly between electricity production and process heat supply. The guiding parameter here would be the demand for process heat on the part of the chemical plants. Surplus power would be available for electricity production. The electricity generated would also be primarily purchased by the process plants.

The interface to the public grid is necessary to balance the energy demand of the consumers with the supply. At times of lower process heat demand, electricity production would increase and could exceed the electricity demand of the consumers. The surplus power would then be fed into the public grid. Conversely, electricity would be drawn from the public grid to cover the shortfall in electricity demand if, at times of high demand for process heat, the company's own electricity production had to be reduced to cover the demand of the connected process plants.

The control of the coupled energy grid is a complex task that would have to be carried out by a central grid management system. The foreseeable demand for thermal and electrical power would have to be fed into to management system by the grid operator, so that the utilisation of the power generation capacities and the external power purchase can be planned. In the event of unforeseen disruptions, this management system must be able to control all connected grid capacities in such a way that the electricity and heating grids are quickly restored to a stable state that meets demand.

3.1.3 Interface of safety, security and safeguards

The presence of co-generating facilities in the vicinity or on the site of a nuclear reactor poses challenges beyond its safety.

The connection between the nuclear reactor system and the co-generating facility could enable pathways for endangering the plant that need to be taken into account in security assessment. The example of Stade NPP in Germany show that this is challenge can be met with existing approaches in principle. If the products of co-generation would constitute a major hazard, however, such a situation might require improved approaches.

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Finally, the mere presence of a co-generating facility will not alter the nuclear characteristics of a reactor, the accounting of materials or the surveillance possibilities for safeguards. Consequently, no specific new aspects for safeguards are expected.

3.2 Considerations by IRSN

3.2.1 Context

While cogeneration has never been implemented on French PWRs, non-baseload operation has been a utility requirement for French nuclear power plants since the 1980s due to the large share of nuclear power in France's electricity supply (around 80 %), the large daily variations and seasonality of electricity demand, the latter being much more pronounced in France than in neighbouring countries (mainly due to the greater use of electric heating in households). More recently, the growth in renewable and non-dispatchable electricity sources has further increased the need for operational flexibility.

As a result, these requirements have been taken into account at a very early stage in the life of the French reactors, in most cases at the basic design stage.

Several types of power variation are implemented, most of them since the beginning of the French PWR programme:

- Quick variations, in order to adapt almost instantaneously to electricity demand: Primary Frequency Control, automatically driven by the grid frequency, and Remote Load Dispatch Control, automatically driven by a signal from the grid operator. Together, these two modes allow up to 10 % variation in rated thermal power (RTP).
- Daily variations, in order to adapt variations in demand scheduled on a daily basis: Load Following Operation, mostly pre-defined with the grid operator, allows operation between 30 and 92 % RTP for less than cumulated 8 hours over 24 hours.
- Weekly/Monthly variations, in order to adapt to seasonality of the demand: Extended Low Power Operation (ELPO), pre-defined with the grid operator, allows operation between 30 and 92 % RTP for a duration greater than 8 hours over 24 hours.

The following paragraphs summarise the different phenomena assessed by the IRSN as part of the safety demonstration of French PWRs and the way in which their negative effects are mitigated. It is important to note that most of these effects are intrinsic to the design of the French PWRs and may not be transferable to an SMR with a potentially very different design.

3.2.2 Impact of frequent load variations on plant

Load variations have an impact on most of the plant's systems and can adversely affect its operation. The phenomena that have been assessed by IRSN are described in the following paragraphs.

3.2.2.1 Core

Load variations cause power density radial and axial redistributions in the core, which can greatly increase the maximum local power and thus the maximum local temperature or the risk of boiling crisis in the event of an accidental transient. In addition, radial changes in the power density distribution can degrade the representativeness of the core monitoring system (because the relationship between the peripheral core power seen by the ex-core detectors and the global core power is altered).

The power density redistribution is caused by several phenomena:

- In the short term, control rod movements as well as the feedback effects linked with reactor coolant temperature evolution cause axial and radial redistribution.
- In the medium term (a few hours), xenon oscillations following a load change can cause a potentially divergent axial power density oscillation.
- In the long term (a few days to a few months), a power density imbalance due to load variations can cause an imbalance in fuel burnup, leading to a modification of the core response to accidental transients.

Moreover, low power operations lead to a lower xenon density, that can negatively affect reactivity control after a reactor shutdown or in an emergency situation.

3.2.2.2 Pellet-cladding interaction (PCI)

Due to the different kinetics of thermal expansion between the pellet and the cladding, a rapid increase in local power can lead to a hard contact between the pellet and the cladding, resulting in a fracture of the cladding.

This risk is exacerbated by extended low power operation, when both the pellet and the cladding retract due to thermal shrinkage. The hard contact between the pellet and the cladding will then happen sooner during the following power increase.

3.2.2.3 Thermal load and fatigue

The cyclic solicitations associated with load variations, particularly with large pressure and temperature transients, can cause equipment fatigue, resulting in loss of mechanical strength, mostly in secondary circuit. Moreover, variable loads may cause some equipment to operate in an unfavourable operating range, which may lead to vibrations or other nefarious solicitations.

3.2.2.4 Wear and tear

Active components such as valves or control rod mechanisms are more often activated during load variations. This reduces their expected lifespan.

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3.2.2.5 Waste management

Load variations may require an increase/decrease in the boron concentration in the reactor coolant. These operations result in an increase of the volume of effluents that require treatment.

3.2.3 Safety assessment

All phenomena listed above are considered in the safety assessment.

Most of these phenomena, particularly those related to material strength, are considered at the design stage, based on a priori penalising assumptions on load variations. These assumptions need to be regularly reassessed based on feedback from previous years and updated forecasts, and any change may result in the need for an updated safety demonstration.

Maintenance is also adapted to load variations, with increased monitoring of the equipment concerned, or even replacement: equipment that can be easily replaced, such as control rod mechanisms, are assigned a fixed maximum lifetime (which can be defined as a maximum number of solicitations), with systematic replacement at the end of this expected lifespan.

Given how frequent load variations are in French plants, these effects are considered deterministically in the Design Basis Accidents (DBA) studies: for short term effect, the accident is postulated to happen at the worst possible moment of load variations, and for cumulative effect, materials are postulated to have been subjected to all load variations expected at the end of their service life.

Depending on the results of these DBA studies, operational restrictions or limits of operation may be imposed. Any failure to comply with these restrictions is treated as a safety incident. The restrictions depend on the plant model, the fuel management strategies or the moment in the fuel cycle and can be reduced by modifications such as new rod operating modes. For example, the "G mode", introduced in the early 1980s, uses part-strength control rods (Grey rods) to reduce the effect of rod movements on the power density distribution. More recently, the "T mode", to be used in the EPR, introduces automation to further reduce the power imbalance associated with load variations and minimise liquid waste.

In practice, most of these operational restrictions come from the phenomena impacting the core and fuel. This includes limits on the power density imbalance, which must be forecast before any significant load variation, or on the rate of the load variations.

A special case is the pellet-cladding interaction: this risk is assessed directly and at all times by means of an indicator ("credit K[4]") representing the margin to cladding rupture in the event of an accidental power transient, this margin being evaluated by dedicated calculations. Full power

[4] The "credit K" is representative of the safety margins with respect to the risk of rupture of the fuel assembly claddings by interaction between the pellet and the cladding, assisted by stress corrosion. It's connected to the number of days authorized at reduced power operation.

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operation causes the indicator to increase, while ELPO causes it to decrease. If the indicator falls below a predetermined value, ELPO is prohibited.

An additional parameter that will be exacerbated to SMRs, due to their short active length and the deformation of axial power distribution induced by load variations, is the avoidance of boiling crisis. As boiling crisis is a local phenomenon related to local heat flux and overall axial flux shape, the determination of the associated critical heat flux requires a reliable methodology. This evaluation is primarily based on experimental data representative of the fuel assembly. This database is not easily transposable to SMRs.

3.2.4 Conclusion

Load variations cause various phenomena on the nuclear plant, and all of them need to be considered in the safety demonstration.

It is important to note that most of these effects are intrinsic to the design of the plant. The paragraphs above list these phenomena on the French PWRs, but most of them are probably not directly transferable to an SMR with a potentially very different design. The design of the reactor is then an important parameter to deal with non-baseload operations.

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4 First suggestions for a methodology of safety margin assessment

From the previous discussion, it appears clear that *"the methodology for assessment of relevant physical parameters and safety margins of the SMR"* (TANDEM Grant Agreement) in a cogenerating application, being one of the targets of the TANDEM Project, must be inspired to previous work that has not yet focused specifically on the consequences that cogeneration has on the safety level of LW-SMRs. Moreover, it must be noted that there is still work in progress on the adaptation to small modular reactors of the usual safety principles and practices routinely applied to large size reactors.

In this context, which needs to be consolidated by further elaboration at the international level, the TANDEM project can contribute on the basis of the above considered information and of the further work to be developed in its frame, by suggesting some points of attention. While specific considerations will be developed in a subsequent phase, in which the reference SMR and the related cogenerating application will be better clarified, at the moment it is possible to highlight some issues which need to be discussed in this process, thus suggesting a first sketchy path for the assessment methodology.

In view of this elaboration, a first assessment of potential issues can be performed by considering the WENRA safety objectives, as summarised in WENRA (2021), and discussing which features of the cogeneration application impact on the SMR safety margins, in addition to what already suggested by WENRA for the general application to SMRs. In this purpose, it is useful to report below the list of these objectives:

- O1. Normal operation, abnormal events and prevention of accidents;
- O2. Accidents without core melt;
- O3. Accidents with core melt;
- O4. Independence between all levels of defence-in-depth;
- O5. Safety and security interfaces;
- O6. Radiation protection and waste management;
- O7. Leadership and management for safety.

As previously discussed in this report, the interaction with the cogenerating application, on one side, and with an electrical grid dominated by RES with a limited availability of storage (for electricity and heat) on the other, may impact directly on the first safety objective. However, a deeper understanding must be developed in relation to the impact that the coupling with the cogenerating application has on the other objectives and, in particular, on the objective 4, related to the independence of the defence-in-depth levels, as well as on objective 5, on safety and security interfaces, and objective 6, on radiation protection and waste management. At the moment, these non-trivial links can be difficult to be identified, but the methodology of assessment should be able to shade better light on them.

A second screening for possible concerns can be performed by considering the mentioned SMR Regulators' Forum (2021) categories of issues, reported hereafter for convenience:

- First of a Kind (FOAK) issues;
- Multi-unit/multi-module issues;
- Passive Safety;
- Exclusion of Faults from Safety Analysis;
- Severe Accidents and Design Extension Conditions.

As previously mentioned, multi-unit/multi-module issues seem to be more directly involved by the interaction with external processes and with the electrical grid which may introduce accident initiators. However, more in general, FOAK issues should be attentively considered, owing to the lack of experience in interfacing SMRs with other processes in cogeneration; in fact, it is clear that a very limited amount of information is available on the possible consequences of this interaction, suggesting a FOAK nature of the implementation of SMRs in cogeneration.

A third but possibly even more fundamental step can be made in relation to the levels of defence-in-depth (DiD) and to the integrity of the multiple barriers, answering the question of the possible influence that the coupling of the SMR in a cogenerating system may have on each level and barrier. Though there is hardly the need to remind such well known principles and concepts, the levels of DiD as reported in the 2018 edition of the IAEA Safety Glossary are listed hereafter for the sake of convenience:

DiD Levels

Level 1: Prevention of abnormal operation and failures;

Level 2: Control of abnormal operation and detection of failures;

Level 3: Control of accidents within the design basis;

Level 4: Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents;

Level 5: Mitigation of radiological consequences of significant releases of radioactive material.

While an increased frequency of anticipated abnormal occurrences, due to the interface with a grid with a considerable share of RES and with a cogenerating process, may have a direct impact on Levels 1 and 2, the impact on all the other levels of the specific features of the whole plant and of its steady and transient operating modes should be carefully assessed.

In this regard, also in relation to previous considerations, it must be suggested that the flexibility of operation, possibly requested to a nuclear reactor (whether or not SMR) to be operated in a cogenerating application or in load following because of the intermittency of electricity production on the grid, has certainly the effect of multiplying the number of initial conditions to be assumed as relevant in safety analyses. At all the levels in the DiD, this may make these analyses more varied and complex, because of the numerous partial-load starting conditions to be assumed in the envelopment of safety relevant operating situations.

Finally, as anticipated in the previous chapters, the work performed in the frame of the EUROPAIRS Project constitutes an example for the elaboration to be started in the frame of TANDEM about the safety of LW-SMRs in a cogeneration environment. With reference to Deliverable D2.1 of EUROPAIRS, the steps in the analysis methodology can be similar to the path followed in that report for the safety assessment of the (V)HTR system coupled in a hybrid system. In particular, after the definition of the objectives, e.g., in terms of possible independence of the nuclear and the non-nuclear processes, the existing licensing requirements and procedures should be revised considering their adaptation to the cogeneration case. Then, the potential impact of the industrial facility on the nuclear plant and, viceversa, the potential impact of the nuclear plant on the industrial site should be evaluated, finally drawing the necessary conclusions. As mentioned in the previous sections, the methodology presented in the report by IAEA (2022) for assessing and developing safety requirements for innovative nuclear reactors, including SMRs, represents an additional, very recent and authoritative reference to be considered in applying a rationale similar to the one that the EUROPAIRS project has developed for HTRs.

In the light of this information, the above mentioned aspects and issues will be covered at the extent possible in the frame of TANDEM by Deliverable D4.2 (Identification of potentially impacted safety margins and methodology for safety analysis of a SMR integrated in a hybrid system) and D4.3 (Report of operational transient safety case Studies for a SMR with cogeneration), to finally reach sound conclusions in D4.4 (Report of operational Design Basis Accident case studies for a SMR with cogeneration), eventually drawing the lesson learned in D4.5 (Summary report on safety case studies for a SMR with cogeneration).

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5 Conclusions

In this report, the status of the safety analysis in Europe from the operational flexibility and cogeneration viewpoints has been addressed, aiming to pave the way for the development of a methodology to assess the potentially impacted safety margins of the SMR when integrated in a hybrid energy system.

The search for previous studies in this field mostly identified an extensive work performed in the frame of the NC2I platform, concerning (V)HTRs coupled in cogeneration applications. Limited information was available on LWRs and more specifically for LW-SMRs, though some nuclear plants are operating in cogeneration and experience in this regard is being accumulated. This configures the present work at some extent as the start or the further consolidation of a line of research that will be hopefully useful for the adoption of light water small modular reactors in the future energy mix in Europe.

It was noted than not only the inclusion in a cogeneration application, but also the interfacing with an electrical grid dominated by intermittent renewable energy sources and storage systems will need to be carefully assessed for the consequences that both may have on the safety margins of the nuclear reactor. Though in the frame of TANDEM the issue of cogeneration is mostly targeted, the context of inclusion of the cogenerating system inside an electricity grid must be borne in mind for requirements in terms of flexibility that it may pose to it.

The presentation of the considered sources of information has been wilfully conceived as a sort of reading guide of them, with several verbatim quotations, avoiding as far as possible to elaborate the content in own words in order to minimise spurious interpretations or biases. It is believed that for the elaboration of the next deliverables in WP4 (D4.2 to D4.5) the same sources will need to be considered again in greater details, in view of the elaboration of a methodology for the assessment of the safety margins affected by the inclusion of the SMR into a hybrid system.

The methodology of assessment, briefly introduced in Chapter 4, represents just a sketchy and preliminary reflection on the messages collected from the considered sources, needing further work to be cast into a convincing tool for analysing the safety margins of the LW-SMR when impacted by the inclusion into a hybrid cogenerating system. Since the very work of adaptation of safety concepts and principles to SMRs is still underway worldwide, the further work to be performed in this regard will have to take into account the evolving context in which the safety of innovative nuclear reactors is being studied.

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