D5.3

Main HOF issues regarding multi-unit & cogeneration in LW-SMRs

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4. Summary

This deliverable is part of the work package number 5 (WP5) focusing on issues raised by LW-SMRs regarding Human and Organizational Factors (HOF). This WP5 consists of four tasks; this work is part of Task 5.1, which examines the effects of three “innovations” introduced by small modular reactors (SMRs) on control room operations. These three “innovations” are the multi-unit configuration, cogeneration, and the increased reliance on passive safety systems. The effects of the latter were studied, and the publication of the results constituted the first deliverable of this Task 5.1: "D5.1. Main HOF issues regarding passive safety systems in LW-SMRs”.

This report examines the challenges related to Human and Organizational Factors (HOF) in the development of Small Modular Reactors (SMRs), with a particular focus on cogeneration and multi-unit operation. While these technologies promise greater flexibility and improved economic performance, they also significantly transform operators’ work, especially in terms of supervision, coordination, and priority management. Drawing on a case study and a literature review, the report primarily emphasizes cogeneration—an area that remains underexplored—in order to analyze its impact on control room activities and to support the early integration of HOF considerations into SMR design.

5. Keywords

Control room operations, Multi-unit supervision, Cogeneration, Human activities, SMRs.

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6.Abbreviations and acronyms

Acronym	Description
C&D	Communication & Dissemination
HOF	Human and Organizational Factors
NPP	Nuclear Power Plant
WP	Work Package

7. Introduction

The development of Small Modular Reactors (SMRs) relies on design features such as reduced reactor size and power, an increased reliance on passive safety systems, higher levels of automation, and, in many concepts, the integration of multi-unit operation and cogeneration applications. These characteristics are commonly presented as enabling greater deployment flexibility and improved economic performance through simplified systems, reduced operating and maintenance costs, and smaller operating crews (Blackett et al., 2022).

However, as highlighted in the Human and Organizational Factors (HOF) research literature, these technological and architectural evolutions raise a series of interrelated challenges that go beyond intrinsic safety performance. They profoundly affect operational activities, organizational arrangements, and human–system interactions in control rooms. Within the EASI SMR project, and more specifically in the context of WP5 dedicated to HOF issues, three major challenges have been identified as shaping operator activities and safety management in SMRs:

1. the increased reliance on passive safety systems,
2. the operation of multiple reactor units from a single control room,
3. and the integration of cogeneration missions alongside electricity production.

The first of these challenges, linked to passive systems, was addressed in detail in a previous WP5 report (Poret et al., 2025), focused on Thermal Hydraulics passive safety systems based on natural circulation. The present report deliberately concentrates on the two other challenges. This report was initially intended to jointly analyze cogeneration and multi-unit operation based on a reference situation. However, the site considered in this report was initially identified as suitable for multi-unit operation due to the presence of two small reactors, did not feature multi-unit control, as each reactor had its own control room. On the other hand, it proved particularly valuable for analyzing the effects of cogeneration on control room operations. Easier access to field data on cogeneration, as opposed to multi-unit modality, is an advantage for this report because, as will be discussed, the literature on multi-unit modality is much more extensive than that on cogeneration. Field data on cogeneration helps fill a gap in literature. Consequently, the report focuses primarily on cogeneration.

Previous studies on advanced nuclear control rooms have shown that increasing automation and system simplification do not reduce the role of operators but rather transform it, requiring greater emphasis on supervision, anticipation, and system understanding (Hugo, 2006). These changes take on even greater significance in the

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context of small modular reactors (SMRs), where reduced staffing levels, the supervision of multiple units, and the diversification of operational objectives impose new demands on the performance of operational activities, whether cognitive, organizational, or related to the coordination of operating teams. As highlighted by Blackett et al. (2022), design assumptions regarding reduced workload and staffing levels can, if not carefully evaluated, create new vulnerabilities for human performance and nuclear safety.

Against this backdrop, the present report situates multi-unit operation and cogeneration as key challenges for HOF in SMRs, directly connected to the objectives of nuclear safety. By examining how these configurations may influence operators' ability to monitor plant states, diagnose abnormal situations, coordinate actions, and manage competing operational priorities, the report aims to support the early integration of HOF considerations into SMR design and operational mode definition within the EASI SMR framework.

This report contributes to the field by describing how cogeneration is reshaping control room work at the organizational and operational levels, based on a detailed analysis of a case study. It offers empirical insights into risk prioritization, anticipation of transients, and coordination of supervision, aspects that remain largely unexplored in the existing literature on small modular reactors (SMRs). Throughout this report, cogeneration and multi-unit supervision are analyzed not as technical features, but as configurations that may transform operators' activities and decision-making processes and introduce new coordination challenges that must be considered from the design phase onward. Finally, throughout this report, cogeneration is analyzed empirically, while the multi-unit system is addressed primarily through the literature and applicable lessons learned.

This report is structured as follows:

- Section 8 situates cogeneration and multi-unit operation among the main challenges posed by SMR designs from a Human and Organizational Factors perspective, building on existing research on passive safety systems.
- Section 9 presents the methodological framework, grounded in activity-centred ergonomics, and details the data collection and analysis process based on a reference situation and a targeted literature review.
- Section 10 describes the reference situation used to explore cogeneration activities and supervisory arrangements.
- Sections 11 and 12 analyze the HOF issues associated with cogeneration and multi-unit supervision respectively, focusing in particular on risk prioritization, anticipation of transients, information management, and coordination across roles

8.From design features to HOF issues in SMRs

This report focuses on the operational activities of control room teams and examines, from a Human & Organizational Factors (HOF) perspective, the potential effects of multi-unit supervision and cogeneration on human actions and activities, as identified within Work Package 5 of the EASI-SMR project. The main objective is to understand how they redefine operator tasks, organizational arrangements, and the management of normal and abnormal conditions and, viewed through this lens, what effects they may have on safety.

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8.1. Multi-unit operation: workload, coordination, and safety margins

Operating multiple nuclear reactors from a single control room represents a departure from the paradigms of single-unit operation. Contrary to the commonly held assumption that simplifying systems and automation reduces the workload, some authors (Blackett et al., 2022; Hugo, 2006) show that multi-reactor supervision transforms the nature of the operator's work rather than lightening it.

The HOF literature (Blackett et al., 2022; Boring et al., 2019; Hartmann et al., 2024; Hugo, 2006; Pokhrel, 2025; Stevens-Adams et al., 2015), which addresses the effects of multi-unit operation on operators' work, examines this phenomenon primarily through the concept of workload. Hugo (2006) notes that transient or incidental situations can generate sudden peaks in cognitive load, particularly when multiple units are operating simultaneously or exhibit correlated disturbances. Hartmann et al. (2024) thus demonstrate that the acceptable limits on the number of reactors supervised by a single operator are not determined by nominal routine operations, but by the ability to manage degraded scenarios, including simultaneous or near-simultaneous events across multiple units.

This issue ties in with the work of Boring et al. (2019) on the level of automation in advanced control rooms. The authors show that humans remain indispensable for overall supervision, managing unforeseen situations, and decision-making, hence the importance of "keeping the operator in the loop" through transparent and relevant automated information. In a multi-unit environment, the operator may not necessarily have a detailed view of all interactions but must have sufficient information to understand the overall state of the system and safety priorities, which tends to increase the complexity of supervision.

Research conducted in other highly automated fields shows that an increase in the number of supervised systems raises the risk of missing weak signals and delays in detecting emerging anomalies (Pokhrel, 2025; Stevens-Adams et al., 2015). When applied to SMRs, this phenomenon can lead to a gradual erosion of safety margins if operators do not have interfaces and organizational mechanisms that allow them to quickly identify which module requires priority attention.

Beyond individual factors, collective coordination becomes critical in multi-unit configurations with reduced crews. The work of Weick & Roberts (1993) on the "collective mind" shows that safety relies on attentive and continuous interaction among team members, made possible by cognitive redundancies, overlapping activities, and a shared understanding of the system's states. However, the staff reduction assumptions associated with SMRs risk undermining these mechanisms by limiting opportunities for cross-checking and collective regulation (Blackett et al., 2022). This appears to run counter to key lessons learned from the Three Mile Island accident, which led to the creation of independent safety oversight functions and dedicated safety engineering roles precisely to ensure multiple, independent assessments of a given situation and to foster constructive challenge (Jacquemain, 2013; Libmann, 1997). Reducing such redundancy could therefore be interpreted as a regression in safety practice rather than an improvement

Finally, from a design perspective, several authors (Blackett et al., 2022; Boring et al., 2019; Hugo, 2006) emphasize that safety in multi-unit operation does not depend solely

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on the number of reactors, but on the quality of ergonomic and organizational choices[1]: differentiated and prioritized display principles, clear rules for inter-unit prioritization, procedures adapted to multi-event scenarios, and team structures allowing for rapid reallocation of roles in degraded situations (Boring et al., 2019; Hugo, 2006). Without these conditions, multi-operation can create systemic vulnerabilities that are difficult to compensate for after the fact.

Some examples of research questions related to these aspects of multi-unit supervision and operation include:

- How do operators prioritize actions and allocate attention across multiple units under normal and abnormal conditions?
- Under what circumstances do multi-unit events create risks of cognitive overload or delayed response with potential nuclear safety consequences?
- What organizational structures, procedures, and HSI design principles are necessary to support safe multi-unit operation?

8.2. Cogeneration: expansion of the operational scope and new interfaces

Cogeneration is one of the main arguments in favor of SMRs, as it extends their use to functions such as district heating and hydrogen production in industrial processes, for example. According to Featherstone (2020), cogeneration involves using energy from a combustion source for at least two applications simultaneously. Most of the time, this involves generating electricity in parallel with an application requiring industrial heat. IAEA defines nuclear cogeneration as “the simultaneous production of electricity and heat or a heat-derivative product from an NPP” (IAEA, 2020, p. 3) and specifies that “Instead of being rejected, this heat [heat rejected from NPP as waste] still retains the required energetic pressure and temperature (gained during the conversion process to power), which may be utilized to produce heating or cooling, or as an energy source to produce fresh water, hydrogen or other important products such as oil and synthetic fuel” (IAEA, 2019, p.3).

More specifically, and in the context of SMRs, the applications considered for simultaneous use with electricity production are urban heat production, hydrogen production, and water desalination. From the perspective of HOF, however, this diversification should not be analyzed as a mere functional extension, but rather as a reconfiguration of operational activities and their objectives (IAEA, 2019). The safety literature emphasizes that such hybrid configurations can create decision-making tensions when objectives diverge, particularly in disruptive situations (Hollnagel, 2014). IAEA literature (2019) notes that cogeneration involves the oversight of additional systems, which are often characterized by physical dynamics that differ from those of nuclear systems, and by shared responsibilities with non-nuclear entities. Furthermore, the integration of non-nuclear systems into a nuclear facility must be systematically analyzed from the perspective of overall risk, including organizational and human effects, and not solely technical interfaces (IAEA, 2005, 2019). This entails stringent

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[1] This point has been constated while we have visited the automated subway line control room where operators used several technical and organizational disposals (captors, video, alarms, supervision levels, etc.) to monitor the different units (trains) in various stages and to follow travellers' interactions.

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requirements regarding control room design, integrated procedures, and operator training for situations involving conflicting objectives.

Some examples of research questions related to these aspects of cogeneration include:

- How does cogeneration affect operators' decision-making when safety, electrical production, and heat or process supply objectives diverge?
- What new organizational interfaces and coordination mechanisms are required to ensure that nuclear safety remains the overriding priority?
- How can control room design and procedures support safe operation in integrated nuclear–industrial systems?

8.3. Contribution to Nuclear Safety within the EASI-SMR's WP5 framework

Without prejudging the intrinsic benefits or limitations of SMRs, this report adopts an ergonomic approach to safety, according to which the performance and safety of complex systems arise from the dynamic interplay between technologies, organizations, and human activities (Daniellou, 1996; Daniellou & Garrigou, 1992).

By focusing on the control room operations of cogeneration and the configuration of multi-unit modules, the report aims to identify potential vulnerabilities early on or specific areas of concern related to changes in control room operations, before they are set in stone by irreversible design choices or organizational assumptions. This approach is consistent with the principles of design ergonomics, which emphasize the integration of knowledge about actual work from the early stages of industrial projects (Daniellou, 2004).

From a safety perspective, the main challenge is not only to prevent individual failures, but to preserve the system's ability to cope with the unexpected (Hollnagel, 2014). Multi-unit and cogeneration configurations can enhance overall robustness if designed to support teams' ability to anticipate, coordinate, and adapt (Boring et al., 2019). Conversely, they can undermine this capacity if they are based on unrealistic assumptions regarding workload, cognitive availability, or the substitutability of humans by automation (Blackett et al., 2022; Boring et al., 2019).

Thus, in line with the objectives of EASI SMR's WP5, this report aims to contribute to a HOF analysis, as applied to SMRs by exploring the potential effects of cogeneration and multi-unit configurations on operating activities. Rather than setting out formalized requirements, which are difficult to establish given the current state of knowledge and available data, the goal is to document and analyze these effects to foster constructive criticism. The goal is to help designers, operating companies, and safety authorities identify the key questions to ask prior to project initiation, by grounding design decisions in a more nuanced understanding of operators' actual work and its determining factors.

9.Methodology

This work falls within the field of an activity-centered ergonomics, as developed from various foundational works (Daniellou, 1996; Daniellou & Béguin, 2004; Falzon, 2004; Rabardel et al., 2002; Wisner et al., 1997). In this activity-centered ergonomics, the concept of activity is central: understanding this activity from the perspective of the participants who engage in it is essential to its analysis.

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More specifically, the activity is approached from a constructivist perspective (Hutchins, 1995; Mead, 1985; Piaget, 1937; Suchman, 1999; Vygotski, 1994),which means that human activity is not reduced to the mere execution of prescribed instructions but understood as a situated and dynamic process of sense-making, in which actors actively construct meaning through their interactions with the environment, tools, and others. Within this framework, actors interpret situations based on their experience, the constraints and resources of the context, and develop compromises to maintain both safety and system performance (Hollnagel, 2014; Rasmussen, 1997).

Building on the first report dedicated to passive safety systems (D5.1), safety and reliability are thus viewed as emergent properties of socio-technical systems, resulting from the interplay between technical devices, work organization, and human activity.

9.1. Data collection methodology

9.1.1. Identifying a reference situation for collecting data on future work

In line with this constructivist approach, the methodological framework does not aim to verify whether situations conform to a predefined model or to assess nominal performance, but rather to understand how situations are actually constructed, understood, and managed by the actors involved. Data collection therefore relies on qualitative methods that provide, as much as possible, insight into the reasoning, interpretations, and trade-offs made in real-world situations. Since SMRs are currently in the design phase, it is not possible to observe operators’ actual work in such facilities; we therefore relied on a well-established methodological approach in work ergonomics that involves identifying a “reference situation” (Daniellou, 2004; Daniellou & Garrigou, 1992). A reference situation is an existing situation that shares similarities with the future situation currently being designed and can therefore serve as a basis for identifying potential characteristics that will emerge in the future situation. This reference situation must therefore be as close as possible to the future situation currently being designed. That is why the researchers explored several possible situations (a public transit network control room, an aviation control room) before settling on a specific one, described in Section 10: this situation refers to the operation of the French-nuclear-powered aircraft carrier *Charles De Gaulle*, and more specifically from the systems that enable aircraft launch operations. In fact, while the idea was to identify a relevant reference situation for studying multi-unit supervision, the researchers concluded that the “unit” in question in the public transit network and aviation sectors did not share sufficient similarities with the “unit” referred to in the SMRs. For this reason, they did not pursue further analysis of these two situations, opting instead for the French-nuclear-powered aircraft carrier *Charles De Gaulle*, in which the “unit” in question was virtually identical, as it consists of nuclear reactors smaller than conventional reactors.

It also seems important to us to clarify a point here, one that was already mentioned in the introduction. The reference situation ultimately selected for this research project, namely the French nuclear-powered aircraft carrier *Charles De Gaulle*, was initially identified for its multi-unit nature but ultimately proved more relevant in the context of the study of cogeneration.

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The data was collected through a visit to the French nuclear-powered aircraft carrier *Charles De Gaulle*, as well as to the training simulator, and interviews[2] with professionals who worked on that facility. More specifically, we adopted a three-step data collection methodology:

- First, prior to the visit of the French nuclear-powered aircraft carrier *Charles De Gaulle*, we conducted exploratory interviews with professionals who had worked on this facility. These interviews, which could be described as semi-structured interviews, are an essential step in gaining an understanding of the field, refining research questions, and preparing for the site visit;
- Next, the visit provided an immersion in the real-world context in which these activities take place, which is essential to our theoretical grounding. Our primary objective was to visit the control rooms of the ship's reactors and gain a clearer understanding of the related operations, even though the visit was broader in scope. This visit provided ample opportunity for additional information and discussions with professionals of the on-site teams, helped deepen our understanding of the actual operations and lay the groundwork for follow-up interviews with professionals who had worked on this facility;
- These follow-up interviews were the last step of our data collection methodology. Their objective was to revisit more specifically certain elements or specific work situations mentioned during the initial interviews and/or the site visit that were deemed relevant for the subsequent analysis, as well as to clarify the strategies implemented by the professionals to address the identified constraints, for example.

In steps 1 and 3, we interviewed a total of four people: three of them were interviewed in both steps, while the fourth was identified later and was therefore interviewed only in step 3. During the visit, we spoke with about ten people, though these were not formally scheduled interviews. The aim was to encourage them to speak freely so that we could gain a deeper understanding of their activities, while taking care not to disrupt their work too much.

9.1.2. Conducting a literature review

In parallel with the identification and analysis of this reference situation, a literature review was conducted to assess the state of the art regarding HOF research that may have been conducted to date on the effects of multi-unit supervision and cogeneration on work activities (control room operations), not only in the nuclear sector but also in other sectors that may share similarities.

9.2. Data Analysis Methodology

Given the limited number of academic studies specifically addressing cogeneration and its impact on the work of control room professionals, the data analysis was primarily guided by the insights revealed by the reference situation. The field data was thus analyzed inductively to identify the key themes of the activity, as expressed and implemented by the participants. In a second step, these themes were compared with the existing literature—when available—not with the aim of applying pre-established

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[2] Interviews are a key source of information for understanding how people form their understanding of how systems operate, identify significant situations, and make sense of the events they observe.

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frameworks, but rather to foster mutual enrichment and dialogue. This approach was driven not only by the limited amount of relevant literature, but also by the exploratory nature of the study.

This process made it possible both to situate the empirical results within the context of available knowledge and to contribute to documenting a field that remains poorly explored. It should also be noted that there is a much more extensive body of literature on the multi-unit supervision than on cogeneration in relation to control room operation. Since the main objective of this report is to draw lessons from a reference situation in comparison with the available literature, there is an imbalance between the two sections of this document.

10. Presentation of the reference situation

The reference situation considered in this study is based on the operation of the French nuclear-powered aircraft carrier *Charles de Gaulle*, whose primary military purpose is to support aircraft operations. Its two reactors' operational purposes also include electricity generation, ship propulsion, and freshwater production.

The steam required for the various applications we have just mentioned is generated by two nuclear reactors on board. Since the aircraft carrier's operational requirement is "to be capable of launching 35 to 40 aircraft weighing 15 to 25 tons, day or night, in sea conditions up to force 6" (Galbet, 1998) these auxiliary systems include two steam catapults, which are essential for launching aircraft from the flight deck.

Steam production is organized into two distinct but similar units, each corresponding to one nuclear reactor. Each reactor is operated independently and is associated with its own dedicated control room. Each of these control rooms is staffed by a team of operators and a first-line supervisor (L1 supervisor) responsible for the safe operation of that specific reactor. Within each team, operators perform complementary roles related to reactor control, mechanical systems, and electrical systems, reflecting the need to simultaneously manage the nuclear reaction, energy conversion, and energy distribution processes.

Each control team operates largely independently with respect to its own reactor, as the two nuclear units are physically and operationally separated, even though they contribute jointly to the overall energy production of the ship. Beyond this first level of supervision, a second supervisory level (L2 supervisor) oversees both units simultaneously, maintaining a global view of the energy production system. This supervisor is supported by additional operators responsible for cross-cutting functions such as auxiliary systems and radiological protection, which are critical in a nuclear propulsion environment. A third-level supervisor (L3 supervisor), who is not stationed in the control rooms but at the bridge, has an overview of all operations. He heads the operational chain for navigation and oversees the boat's overall operations.

A key feature of this system lies in the multiple uses of the steam produced by the nuclear reactors, which differ significantly in their temporal dynamics and operational constraints. Part of the steam is used in a continuous manner for ship propulsion, ensuring steady mechanical power to the propulsion turbines, as well as for onboard electricity generation and freshwater production through desalination processes. These

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functions require a relatively[3] stable and uninterrupted supply of steam, contributing to the baseline energy demand of the vessel.

In parallel, another use of steam is intermittent and highly demanding: aircraft-launch catapults. It operates according to a principle common to modern aircraft carriers. High-pressure steam is first accumulated in dedicated reservoirs and then released into cylinders located beneath the flight deck. The rapid expansion of the steam drives pistons connected to a shuttle, which accelerates the aircraft from rest to take-off speed in a very short distance, typically around 75 meters and within a few seconds. This process requires storing energy beforehand and releasing it almost instantaneously, illustrating a form of discontinuous and high-power demand.

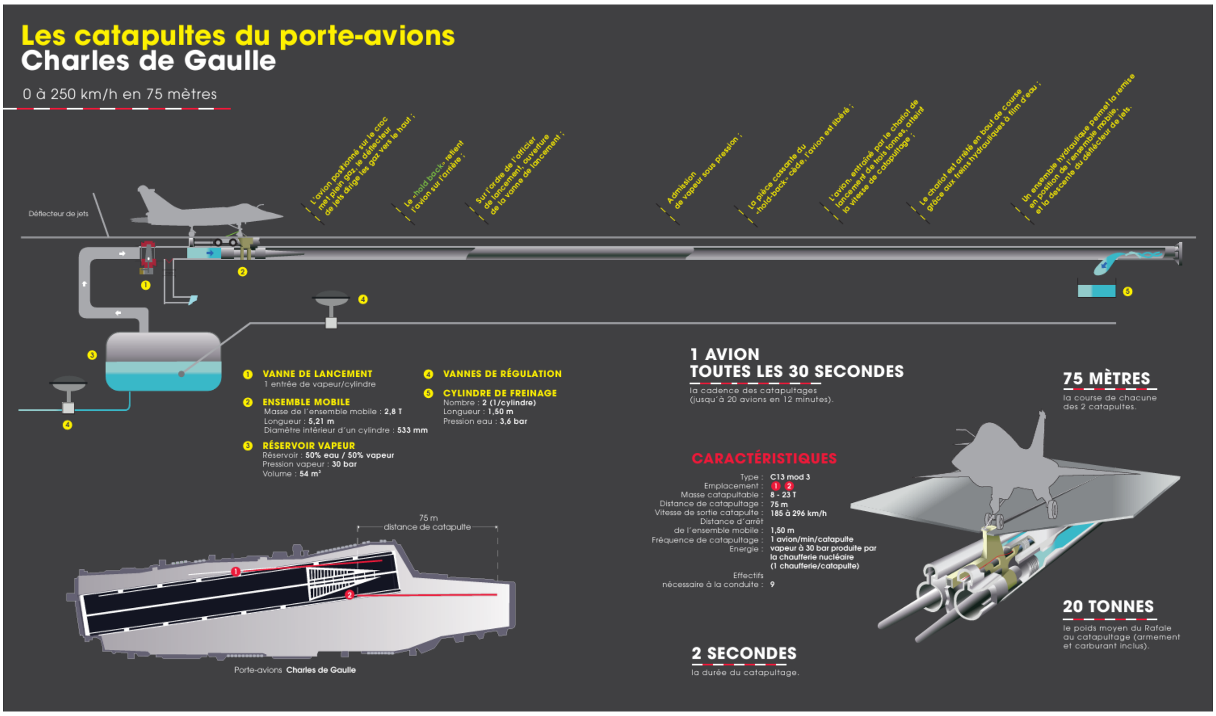

Figure 1 Illustration of how the catapults on the aircraft carrier Charles de Gaulle work (https://www.colsbleus.defense.gouv.fr/sites/default/files/2021-05/CatpulteV12.pd)f

Thus, while propulsion, electricity generation, and freshwater production rely on continuous steam consumption, the catapult system introduces sharp, short-duration peaks in demand. It periodically draws a significant quantity of stored steam, converting it into mechanical energy over a very short time interval (on the order of a few seconds) to achieve the acceleration required for aircraft launch. This combination of continuous production and intermittent high-power demand creates specific coordination challenges between operators and supervisory levels (Team, 2026).

We will now present the results of the analysis of the data collected from this reference situation. We first present the results related to cogeneration (Section 11) and then those related to multi-unit supervision (Section 12). As noted earlier, the section on cogeneration is more extensive because the empirical data collected in the reference situation primarily supported this topic. Furthermore, whether in Section 11 or 12, the

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[3] The vessel's propulsion can cause significant fluctuations

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presentation of results follows the same logic: we first present the results from the reference situation before drawing conclusions for future SMR operating situations.

11. HOF issues related to cogeneration

There are three results related to cogeneration, which are presented in subsections 11.1 through 11.3.

11.1. Risk prioritization & its organization

11.1.1. An existing organizational mechanism that emphasizes the need for prioritization and coordination

An existing organizational mechanism within the reference situation highlights both the need to prioritize among different uses in certain situations and the importance of clearly defining the scope of each person's responsibilities in such situations. This organizational mechanism shows how competing operational requirements related to different uses of steam may necessitate explicit decisions regarding the sequencing and continuation of activities, especially under constrained or degraded conditions, but also under normal operating conditions. Within this arrangement, a key mechanism relies on the distribution of responsibilities and decision-making powers between different supervisory levels. Four levels of operation were thus identified in this reference situation.

Level 1: For the **first level**, operational targets, such as speed order and aircraft-launch catapults sequence within a given timeframe, are defined and communicated by a dedicated department in charge of air operations. These instructions structure routine operations but are not absolute.
Level 2: In the event of an incident or accident on site, shift teams are required to depart from these initial objectives to mitigate risks as effectively as possible. However, the coordination of the parties involved, and the management of risk prioritization do not stop there.
Level 3: When these different uses of steam create heightened or widespread risks to personnel or equipment, particularly when such risks fall outside the direct control of the reactor shift teams, the L3 supervisor may decide to temporarily prevent the teams from taking corrective action. This overrides the first and the second level and switches to the third level. This third level illustrates two key principles underlying the functioning of onboard operations: "competition among safety measures" and "dynamic subsidiarity" For the first one, L3 supervisor has "overall situational awareness" (L1 supervisor), allowing him to prioritize risks ship-wide. In this context, corrective actions for the affected reactor are not necessarily a priority. Teams are instructed to maintain the situation for a duration determined by the L3 supervisor, even if this results in equipment damage. These decisions remain within the safety margins defined by the system designer and do not override core reactor protection mechanisms. Regarding the second principle, known as "dynamic subsidiarity," the L2 supervisor authorizes corrective actions only after obtaining approval from the L3 supervisor when such actions could impact the ability to fully meet operational needs. In operations not falling under Level

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3, this decision-making level typically falls directly under Level 2 or even Level 1 supervisor. A formal escalation to Level 3 operations, or a departure from this posture, formally signals this change in the decision-making level, reflecting the dynamic nature of subsidiarity.

Here are a few examples to illustrate Level 3. During aircraft catapult launches, priority is given to these launches; if the shift crew encounters difficulties, they must find a way to overcome them to continue producing the steam needed for the launches and ensure the pilot's safety. Meanwhile, L2 report the situation to L3 in order to engage corrective actions as soon as possible, in accordance with the overall safety appreciation and priorities. When operating near another vessel, for example, during a refueling operation, the priority is to maintain propulsion, even if a reactor malfunction occurs. In such situations, numerous cables are stretched between the two vessels, and they are so close together that losing propulsion would risk a collision that could endanger the lives of those on board and cause extensive damage to equipment. The same principle applies during port maneuvers, for example. The principle behind this third level is not to let the machine take over, even if a problem arises. The shift team does not implement Level 2 recovery measures. In this context, priority is clearly given to meeting critical functional needs, particularly when human life or the safety of the facility is at stake. A formal risk-prioritization framework supports these decisions by indicating that, under certain conditions, it may be preferable to accept equipment damage or increased personnel exposure rather than allow risks with more severe or widespread consequences to materialize. This is in no way done at the detriment of safety, since it is the automated systems that ultimately ensure the reactor’s safety. Thus, by design, the automated systems will ensure the highest level of safety given the circumstances, while allowing—to the extent that safety requirements permit—the continued supply of as much energy as possible to meet “operational” requirements (in the broadest sense). The objective is to ensure that activities deemed critical at a given moment can continue to be supported by reactor operation, when an untimely shutdown would itself generate more serious risks.

Level 4: However, if a new event occurs in this type of situation and the L2 supervisor determines that it makes L3 untenable, he informs the L3 supervisor. For example, a fire breaks out in the engine room. The L3 supervisor “[…] may suspend, at the first opportunity […] " (L1 supervisor) the activities involving cogeneration to allow the shift team to secure the situation and then hand back control of cogeneration operations once this is done. For example, during the landing phase, the ship must maintain a certain speed to ensure the aircraft can land safely. This type of situation requires the third level of operation: the engine must provide the necessary power for propulsion even if it encounters difficulties. In the event of a fire breaking out in the engine room, the L3 supervisor can, for example, upon being informed of the fire, readjust his level of risk awareness and update the risk prioritization. In this situation, this would involve contacting the arriving pilots and asking them to hold while the shift crew brings the situation under control. Contacting the L3 supervisor allows them to gain a complete overview of the situation and gives them the opportunity to reassess the risk prioritization. This example clearly illustrates the need for coordination between supervisors at different levels, in other words, between the person who oversees the various units and other steam uses and the person who has oversight and authority over the other steam uses.

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In summary, the delineation of responsibilities and scopes for supervisors at different levels, as well as the formalization of risk prioritization, enable the L1 supervisor (who has an overview of steam usage in their reactor), L2 supervisor (who has an overview of the overall steam usage), and L3 supervisor (who has an overview of the aircraft carrier's activities and thus benefits from the necessary perspective to enable "proper" risk prioritization at the ship level) to coordinate by sharing relevant information to enable risk management adapted to different situations (normal, incidental, accidental) involving various uses of steam. Within this organizational mechanism, the distinction between organic authority, rooted in hierarchical position, and functional authority, limited to a specific domain of expertise or activity, serves as a structuring principle that responds to these operational needs. Combined with explicit risk-prioritization mechanisms, this structure allows roles, responsibilities, and priorities to be reassigned or adjusted with precision. Prioritization is therefore not limited to emergency situations but also applies during certain cogeneration operations requiring heightened vigilance and sustained reactor availability. Overall, this arrangement demonstrates how an organization can and has to prioritize particular activities or uses over others while preserving coordination flexibility and providing teams with sufficient leeway.

11.1.2. Lessons learned and open questions for SMRs

11.1.2.1. Risk prioritization as a key challenge in cogeneration

The institutional literature on nuclear cogeneration appears to establish a clear regulatory framework: nuclear safety must remain the top priority regardless of the energy requirements associated with thermal or electrical uses. The International Atomic Energy Agency (IAEA) thus states that "Whatever the heat demand or the power need from the heat plant, nuclear safety should outweigh any such consideration, as when running the NPP[4] to produce only electricity" (IAEA, 2019, p. 3). This position is also reflected in the requirement that, in the event of an accident, the control and command systems of the nuclear power plant and the heat generation facility be designed such that "the priority should always be given to the safe shutdown of the NPP" (IAEA, 2019, p. 4).

This regulatory framework serves as an essential starting point, but it raises a key question: to what extent is this principle realistic and effective in cogeneration scenarios, where the reactor no longer serves solely the electricity grid but is integrated into broader industrial, regional, or urban value chains?

Existing institutional literature, particularly concerning "risk-informed" decision-making in the nuclear field, shows that while reactor safety remains the top priority, operational decisions are already made within frameworks where risks are prioritized (IAEA, 2005). Prospective studies on nuclear cogeneration suggest that these mechanisms, already in use at current power plants, could be extended to a broader risk scope due to the integration of external energy uses (IAEA, 2019). In fact, cogeneration introduces industrial, commercial, contractual, and even ethical considerations that could complicate the decision-making framework. Contrary to a simplified view that assumes simply shutting down the reactor is sufficient, certain situations make this option costly or problematic given commitments made to partners or customers (heating networks, critical industrial sites, continuity of public services).

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[4] NPP : Nuclear Power Plant

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In this context, risk prioritization is emerging as a key challenge. It is not merely a matter of pitting safety against production, but of managing trade-offs between different types of risks: nuclear risks, downstream industrial risks (especially when the production of steam, heat, hydrogen or electricity, are supplied to an intrinsically hazardous industrial process, such as a high-threshold Seveso chemical plant), economic risks, and societal risks. This multiplicity of issues calls into question the notion of a purely technical or automatic decision and requires reflection on the responsibilities associated with the choices made in both normal and degraded situations.

11.1.2.2. Operational management: proximity, coordination, and reliable communications

Cogeneration in SMRs leads to increased organizational complexity, resulting in a proliferation of decision-making interfaces and stakeholders involved in operations. The interviews highlight the importance of intermediate roles, such as the L2 supervisor, who is responsible for balancing nuclear safety requirements with associated energy needs. These findings echo the work of the IAEA, which identifies coordination challenges among operators, public authorities, and energy stakeholders as a recurring obstacle to the development of cogeneration and district heating projects, due to often fragmented governance (IAEA, 2019). SMR cogeneration exacerbates these challenges by increasing the interdependence of operational decisions.

The interviews also highlight the central role of organizational and physical proximity in operational reliability. The co-location of key actors fosters continuous communication and a shared understanding of the situation, essential conditions for organizational reliability in high-risk systems (Weick & Roberts, 1993). Conversely, remote coordination is perceived as more fragile. Finally, interviewees point to the increased reliance on mediated communication systems as a source of organizational vulnerability. The uncertainty associated with the absence or delay of a response from a remote counterpart illustrates the limitations of these systems in complex contexts. As Hollnagel (2014) points out, the reliability of organizations depends less on the technical performance of communication systems than on the collective ability to interpret, anticipate, and compensate for variations in actual operations, a particularly critical challenge for future multi-unit or cogeneration control configurations.

Ultimately, SMR-based cogeneration does not call into question the primacy of nuclear safety, but it does reshape the practical conditions under which it is implemented. The emergence of issues related to risk prioritization, the growing number of stakeholders, and the increased complexity of organizational interfaces make close coordination among energy, industrial, and institutional actors, in particular, essential. The literature (Hollnagel, 2014; IAEA, 2019; Weick & Roberts, 1993), combined with feedback from the field, suggests that while safety has long been understood as a collective and situated achievement in high-risk systems, SMR-based cogeneration intensifies this dynamic. By embedding the reactor within broader industrial and territorial value chains, cogeneration increases the number of actors, the diversity of risks to be prioritized, and the need for organizational and human mechanisms capable of mediating between competing, and sometimes non-nuclear, requirements.

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11.2. Anticipation of various transients associated with different uses of steam

11.2.1. The importance of anticipating the various transients to avoid exceeding the reactor's operating limits

The cogeneration activity examined in detail, aircraft catapult launches, generates "[…] peaks and power demands […]" (L1 supervisor) that operators must anticipate avoiding approaching operating limits. In the reference situation, these transients depend on multiple factors such as aircraft weight and air speed, resulting in variations in magnitude (depending on aircraft type, load, and weather conditions). In practice, operators must manage two main types of transients: those induced by aircraft catapult launches, which generate short but intense power peaks, and those related to ship propulsion, particularly during acceleration orders, which require more sustained increases in power. These transients may occur independently or simultaneously, creating complex and dynamic power demand situations.

To manage this complexity, coordination is established across several levels through an initial broad schedule developed by personnel with visibility over the different uses of steam. This schedule is then shared with the various stakeholders, who progressively refine it for operational teams. It is reviewed daily and continuously adjusted to account for real-time needs and unforeseen events. This progressive adjustment relies on verbal and written communication:

- between the three levels of supervisors,
- between these managers and the shift teams, and
- within the shift teams themselves, particularly between electrical, machine, and reactor operators.

The sequencing of activities complements this schedule by providing operators with "[…] visibility into activities so they can anticipate certain power consumption needs […]" (L1 supervisor). These transients can be further amplified under specific environmental conditions. For instance, in low-wind situations, the reactor must compensate for the lack of natural lift by supplying additional power for aircraft launch catapults, thereby increasing overall demand and reducing operational margins.

As mentioned in the previous section 11.1.1, certain requests, such as speed orders, are transmitted directly by the L3 supervisor to the control room via a dedicated communication tool. This command is received by the machine operator, who then coordinates with the reactor operator.

For example, when an increase in speed is required the reactor operator proposes or implements this change in the pumping regime based on the information provided by the machine operator. In some cases, machine operators may also need to change the pumping regime for certain circuits.

Although the systems are equipped with automated controls, operators play a key role in managing these situations. Indeed, these verbal exchanges within the team—including between operators—demonstrate a form of coordination that can be described as follows: I announce my intention or the action I am about to take out loud; my colleagues assess the impact this will have on their area of responsibility and take the necessary steps to maintain the highest level of availability and safety. At the same time, supervisors at the L1 or even L2 level maintain a critical overview of the entire process, much like conductors (they can put certain actions on hold or order others to be carried

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out). For major cogeneration activities, particularly catapult launches and propulsion, L1 supervisor evaluates power requirements based on the specified demands and determines the minimum power margin it will maintain at the peak of the transient(s) relative to the reactor's maximum power. In fact, this is a kind of feasibility analysis of the transient sequence relative to the reactor's capabilities. If he detects a difficulty in meeting the requirement as planned, he proposes a sequence or a transient that best meets the requirement without reaching the reactor's limits. This way, a safety margin is deliberately maintained to avoid operating too close to limits, which could trigger automatic controls, complicate operations, or compromise the ability to meet immediate demands.

This highlights the added value of operator anticipation and experience. Automated systems involve response delays and only partially manage the system (e.g., they adjust control rods but not pump speeds). What matters to the L1 supervisor is therefore not only the individual contribution of each activity, but their cumulative and evolving impact on overall energy demand. In this context, the ability to manage combined or amplified transients is essential to avoid reaching operational limits while ensuring both propulsion and flight operations are maintained. Furthermore, knowledge of the facility, experience with past transients, and familiarity with scheduled operations are critical factors in conducting this power requirements assessment. According to one of the L1 supervisors interviewed, a lack of experience will result in the need for larger safety margins.

When the primary pumps operate at low speed and a significant power increase is required, the automated system raises the control rods until it reaches the limits of the current pumping regime. At that point, the ramp-up is interrupted while switching to a higher pumping regime before resuming. If operators anticipate this situation, they can initiate the appropriate regime in advance, allowing the automated system to complete the ramp-up smoothly and autonomously.

In other cases, transients induced by cogeneration activities can be mitigated through operator action. The reactor operator may anticipate the need of power by applying or reducing a little reactivity through a slight adjustment of the control rods. This allows them to stay ahead of the control system, maintain more stable parameters, and ensure smoother transitions that avoid unnecessary stress on the reactor.

Overall, managing these situations is not merely reactive but fundamentally anticipatory. Operators continuously integrate information from flight operations, propulsion requirements, and environmental conditions to preserve safety margins and maintain stable reactor behavior despite inherently coupled and fluctuating demands.

Finally, when several demanding events occur simultaneously and push the reactor to the limits of its capacity, it is possible to rearrange them (by sequencing them). In this way, priority is given to the most critical transient, thereby allowing the system to either better absorb it or avoid actually reaching the reactor's operating limits, which would trigger automated actions.

11.2.2. Lessons learned and open questions for SMRs

The analysis of the reference situation shows that cogeneration generates transients whose management relies heavily on the teams' ability to anticipate variations in power and flow, beyond the responses provided by automated systems alone. This anticipation is supported by a shared and evolving timeline of upcoming activities, developed collectively through iterative planning and continuously adjusted and communicated to

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shift operators. In this context, transients are not merely technical events but coordinated operational sequences requiring anticipation, the preservation of safety margins, and fine-tuning to avoid exceeding operating limits and to maintain stable reactor parameters.

This observation resonates with safety concerns identified by the IAEA (2019), which highlights “the potential for more severe reactor system transients induced by the cogeneration plant, either during normal operation or due to an accident” (IAEA, 2019, p. 22).

The importance of visibility and foresight directly informs the opportunities and challenges associated with the future deployment of SMRs for cogeneration applications. The scenarios envisioned for these reactors, combining electricity generation with industrial heat production, hydrogen generation, or district heating, suggest an increase in both the frequency and the simultaneity of transients across multiple applications or modules. This raises important questions regarding the future division of roles in control rooms.

In the reference situation, responsibilities are distributed across several specialized roles. In contrast, SMR concepts often assume more compact teams, where operators may oversee multiple units while simultaneously handling responsibilities currently assigned to reactor, electrical, and mechanical specialists. This potential concentration of roles calls for careful consideration. It raises critical issues related to maintaining effective oversight, managing competing demands, and supporting robust decision-making in increasingly complex cogeneration environments. Understanding how the redistribution, or concentration, of responsibilities affects coordination, accountability, and decision quality therefore becomes a key issue for future SMR operations.

These considerations also point to a central question regarding the level and nature of automation in SMRs. While increased automation is frequently presented to reduce workload and staffing requirements (IAEA, 2020), the reference situation highlights the essential role of human anticipation in smoothing transients and preserving operational margins. Without early, intelligible, and actionable signals, operators risk being confined to a reactive role focused on managing consequences rather than actively shaping system behavior (Bainbridge, 1983).

This observation aligns with the literature emphasizing the importance of keeping operators “in the loop” and designing automation systems that support anticipation and understanding of future system dynamics, rather than bypassing human intervention (Boring et al., 2019; Hugo, 2006).

Finally, insights from the field underline the continued importance of human expertise in detecting weak signals. During the interviews, the role of the L1 supervisor was particularly emphasized: through continuous monitoring and daily recording of parameters, he can identify subtle anomalies that may not be captured by automated systems. This is also true for operators, although in this case the scope is more restricted. As one supervisor noted, he can “sense” when something is wrong, an ability he considers difficult to replicate through automation alone.

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11.3. Visualization / Overview of the various uses of steam in the control room

11.3.1. A glimpse into other uses of steam, which is indispensable in many ways

What the reference situation revealed, moreover, is how important it is for operators to have access to an overview of other steam uses. This overview can take various forms; in the case at hand, it resulted in the installation of cameras filming aircraft catapult launches, with the video streamed live to the control room.

This overview serves several purposes; first and foremost, it allows for more accurate anticipation of transients. We have seen that the scheduling and sequencing of cogeneration activities allow shift teams to anticipate transients. However, scheduling covers only the catapults launch sequence, that is, its start and end, and not any variations or transitions that may occur during its execution, for example. Having an overview of the cogeneration activity that generates a transient allows operators to be even more precise in their control activities and to manage these transients, which, as we've noted, can be intense, as effectively as possible. Thus, these cameras will not change the operator's actions, but they do allow for better anticipation of transients. In fact, the transient caused by the catapult launch corresponds to the filling of the tank where steam is stored before being released and converted into mechanical energy. When operators confirm via the images that the aircraft has indeed taken off (in addition to having heard it), they are better prepared to manage the subsequent transient.

Second, gaining insight into other uses of steam allows operators to maintain a higher level of vigilance. High level of vigilance cannot be maintained throughout an entire shift; seeing how actions in the control room actually play out allows operators to be more vigilant during those moments. According to one of the supervisors interviewed, this further empowers operators, who naturally maintain a high level of vigilance. Thus, they can ensure that actions taken in the control room achieve their intended objectives and helps give meaning to their work.

11.3.2. Lessons learned and open questions for SMRs

The reference situation highlights a key operational issue: operators benefit significantly from having direct or indirect visibility over downstream uses of steam, as it enhances their ability to anticipate transients, maintain vigilance, and make sense of their activity. While extending such empirical findings to the context of SMRs is not straightforward, particularly given the differences in spatial organization and operational configurations, it nevertheless raises cross-cutting issues that are well documented in the literature on complex systems management.

Cogeneration inherently introduces multiple and potentially competing uses for steam or heat, thereby increasing system complexity and reinforcing interdependencies between subsystems. These challenges are likely to be particularly salient in SMR-based applications, where the diversification of uses is often presented as a key advantage. In practice, SMRs are envisaged for a range of applications, including district heating networks, industrial steam supply and hydrogen production. Each of these configurations introduces specific operational constraints and dynamics that may affect operators' activity.

For instance, in the case of district heating, heat demand varies significantly depending on weather conditions and time of day, potentially generating frequent and sometimes

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abrupt transients that operators must manage (Sánta & Garbai, 2024). Similarly, when supplying steam to industrial users, demand may be influenced by production cycles that are not always directly accessible or visible from the control room. This could raise questions about how operators account for variations in demand that are driven by processes occurring outside their immediate field of observation. In hydrogen production scenarios, electrolysis relies on electricity produced by the system (Hydrogen Production, 2026), which suggests that its operation is closely linked to the availability and allocation of this resource. This raises questions about how different uses of electricity might interact in practice, and how such interactions are considered in operation.

In such contexts, operators may have only indirect or mediated access to information about downstream uses of steam or heat, in contrast with the reference situation where visual feedback, using cameras, and interactions between operators provided immediate confirmation of system behavior. This difference raises important questions regarding how to support operators' understanding of system dynamics when the effects of their actions are not directly observable.

While this study does not rely on the theoretical framework of situational awareness (SA), it is interesting to note that similar phenomena have been analyzed in literature using this perspective. The theoretical framework of situational awareness (SA) developed by Endsley (1995), conceptualizes operator performance as relying on three complementary levels: perception of relevant elements in the environment, comprehension of their meaning with respect to operational goals, and projection of their future states. In the reference situation, the use of cameras directly supported the perception of downstream steam usage, while also contributing to a better understanding of system behavior and to the anticipation of forthcoming transients. More broadly, this illustrates that operators' ability to anticipate and manage transients depends not only on the availability of data, but on their capacity to construct an integrated and meaningful representation of the interactions between electricity generation, heat extraction, and external uses.

Achieving such an integrated understanding in SMR contexts may prove more challenging, particularly when downstream uses are spatially distributed or mediated through technical interfaces. In such cases, alternative mechanisms may be required to bridge the gap between operator actions and their effects in the field. As noted by Stevens-Adams et al. (2015), field crews can act as the "eyes and ears" of operators, highlighting the importance of organizational as well as technological means to support situational awareness. More generally, this raises the issue of how to provide operators with sufficiently rich and relevant information to support anticipation and decision-making, while avoiding excessive informational load.

In this respect, lessons learned from the reference situation suggest that the design of SMR-based cogeneration systems should not only address technical performance and safety, but also explicitly consider how to support operators' activities. This includes enabling them to anticipate the cross-effects of operational decisions, but also to maintain vigilance, a sense of control, and a sense of purpose in environments where the end uses of the energy produced may remain largely invisible. Ensuring appropriate forms of visibility, whether through direct observation, mediated representations, or organizational coordination, thus appears as a key design challenge for future SMR deployments.

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12. HOF issues related to multi-unit supervision

12.1. Prioritization of Information and Construction of a Big-Picture View in Multi-Unit Supervision

Since the two units in the reference situation are not controlled from the same control room, limited insights were obtained regarding the direct effects of multi-unit control at the operator level. However, one role inherently involves a multi-unit perspective: the L2 supervisor.

The interviews highlight that, for this supervisor, access to an appropriate level of detail is essential to "objectify the risk" and maintain a degree of detachment from the immediacy of the situation, which in turn supports decision-making and prioritization. However, this requirement for adjusted information granularity is not specific to this role; rather, it characterizes the entire organizational structure.

At the operator level, detailed monitoring of process parameters enables the identification and reporting of salient information. The L1 supervisor, responsible for a single reactor, selectively requests and aggregates key parameters from operators across different domains (machinery, reactor, electrical systems), thereby constructing an intermediate representation of the system's state. He also incorporates, in parallel, information related to activities (such as aircraft launch sequences for example) that affect the future status of "his" reactor.

The L2 supervisor, in turn, must integrate information across both units as well as other operational activities. At the beginning of a shift, this involves forming a mental representation of the overall situation, including the operational state of each reactor and upcoming activities such as cogeneration tasks like aircraft launch sequences. This representation is deliberately simplified and framed in operationally meaningful terms (e.g., "is it working or not?"), allowing rapid interpretation and action in case of disturbances.

Thus, the ability of the L2 supervisor to maintain a coherent big-picture view does not stem from the direct monitoring of detailed parameters, but from a progressive transformation of information across organizational levels. Each level contributes to filtering, selecting, and structuring information, enabling the construction of increasingly synthetic representations.

This hierarchical regulation of information granularity allows L2 supervisor to oversee multiple units and activities to focus on the overall situation without losing access to relevant details when needed. As emphasized by one L2 supervisor, this also relies on trust in competent personnel at lower levels, ensuring that the process of information selection and transformation remains reliable.

12.2. Lessons learned and open questions for SMRs

The reference situation shows that effective multi-unit supervision relies not on exhaustive monitoring, but on the ability to construct and maintain a simplified yet operationally relevant representation of the overall system state. Crucially, this

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representation does not emerge in isolation: it is the result of a distributed process in which information is progressively filtered, structured, and synthesized across multiple organizational levels.

This point is essential, as it highlights that the “big picture” is not merely an interface feature or an individual cognitive capability, but the outcome of coordinated information processing throughout the system. Each level, operators, L1 supervisors, L2 and L3 supervisor, contributes to this process by transforming detailed data into increasingly abstract and decision-relevant forms.

The importance of maintaining such a global perspective has been widely documented in other domains. In aviation, for instance, “the loss of the big picture by focusing on an immediate problem has led to several accidents” (Hartmann et al., 2024, p. 3)[5]. Similar observations were made during our visit to a public transit network control room, where operators emphasized the need to preserve an overarching situational view despite high levels of automation. Similarly, with regard to our reference situation, we were able to demonstrate that the four-tier structure—based on subsidiarity (Dugué & Petit, 2022): operators plus three decision-making levels—facilitates decision-making at the appropriate level, without “overburdening” the higher level with issues that could cause it to lose sight of the big picture.

These findings resonate strongly with the challenges identified in the literature on SMR operational concepts. Multi-unit control rooms with reduced staffing tend to increase cognitive workload and complicate the management of simultaneous events (Arigi & Eitrheim, 2024; Blackett et al., 2023). In such contexts, operators must dynamically regulate their focus of attention, which makes the availability of appropriately structured information critical. Importantly, the limits identified regarding the number of units that can be safely monitored suggest that performance depends not only on quantitative factors, but also on the system’s ability to support this distributed process of information transformation. In other words, the capacity to maintain a relevant big-picture view is inseparable from the quality of the underlying informational ecosystem (Blackett et al., 2022; Hartmann et al., 2024).

From this perspective, the lessons learned from the reference situation point to several key design considerations for SMR control rooms. First, systems should not only provide synthetic overviews but also ensure that these views are grounded in reliable, well-structured information produced at lower levels. Second, interfaces and organizational arrangements should facilitate seamless transitions between levels of abstraction, enabling operators to access detailed data when required without compromising the overall view.

Ultimately, the design of SMR control rooms should be approached not solely as a matter of automation or unit replication, but as a problem of information architecture: how to organize, distribute, and transform information so that simplified and actionable representations can emerge at higher levels while remaining anchored in operational reality. This also implies a need for clear role definition and coordination mechanisms, ensuring that the collective construction of the system’s state remains coherent in multi-unit configurations.

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[5] The importance of maintaining a big-picture view of the situation was particularly evident in the layout of the control room for the automated subway line, as we observed during our visit.

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13. Conclusion

In line with the objectives of WP5, this report does not aim to define prescriptive requirements at this stage, given current empirical limits. Rather, it contributes to identifying key issues, vulnerabilities, and open questions that should be addressed early in the design and development of SMR operational concepts.

This report examines, from a Human and Organizational Factors (HOF) perspective, the implications of two major operational configurations associated with SMRs, namely cogeneration and multi-unit supervision, on control room activities. Together with previous work on passive safety systems, these configurations constitute three key “innovations” likely to transform operating practices. However, due to methodological constraints and the need for in-depth analysis, each of these dimensions had to be studied separately, leading to the production of distinct reports.

Although this distinction was necessary to precisely identify the specific elements of each of these “innovations,” a joint review of the findings points to the same general conclusion: taken as a whole, these innovations are profoundly transforming the work carried out in control rooms, organizational structures, and the conditions under which nuclear safety is ensured.

The analysis confirms that neither cogeneration nor multi-unit operation can be understood as a simple extension of existing nuclear operating models. On the contrary, they bring about profound changes in the work of plant operators. Cogeneration expands the scope of reactor operation by embedding it within broader industrial, regional, and societal value chains, thereby increasing interdependencies, diversifying stakeholders, and extending the spectrum of risks to be managed. In this context, SMR cogeneration amplifies multi-risk trade-offs, organizational complexity, and interdependencies, challenging how the “safety first” principle is enacted when safety, electricity generation, and heat or industrial supply objectives diverge.

At the same time, multi-unit supervision places strong demands on operators’ ability to maintain a coherent understanding of the overall system state, dynamically allocate attention, and adjust the granularity of information[6]. It also introduces intermediate layers of information and coordination that reconfigure team composition and responsibility allocation, an issue further exacerbated by cogeneration. Together, these configurations call for new coordination mechanisms and control room designs that keep operators central by supporting anticipation, visibility of downstream effects, and informed decision-making in complex socio-technical systems.

Findings from the analysis of a reference situation illustrate these dynamics in detail. Effective cogeneration relies on organizational arrangements that enable prioritization, such as differentiated supervisory roles, explicit delegation mechanisms, structured planning, and continuous cross-level communication, as well as on anticipatory practices that allow operators to manage transients and preserve operating margins. Far from reducing the need for human expertise, these configurations highlight its critical role, challenging design assumptions that equate increased automation with substitution for human activity.

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[6] This point was also confirmed during our visit to the control room of the automated subway line. We observed that the operators relied on a network of cameras set up on the platforms and inside the trains, allowing them to select a viewing angle and focal length suited to each situation. This enables them to access the level of detail required for their work.

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Overall, when the results of the different studies are brought together, they support a conception of safety as an emergent property of socio-technical systems, produced through the continuous interaction between technologies, organizations, and human actors. While SMRs do not call into question the primacy of nuclear safety as a principle, the combined effects of passive safety systems, cogeneration, and multi-unit configurations significantly transform the practical conditions under which this principle is enacted.

In conclusion, the key issues and points for consideration that we highlight in this report enable us to provide answers to the research questions related to cogeneration identified in Section 8.2, namely:

- **How does cogeneration affect operators' decision making?**
    - Exacerbates a multidimensional approach to risk trade-offs (nuclear risks, downstream industrial risks, economic risks, and societal risks), potentially complicating decision-making and putting the "safety first" principle under strain.
    - Increased reliance on context-dependent human judgment, making decisions less standardizable (e.g., role of intermediate supervisors).
    - External constraints (district heating, critical industrial users) may make shutdown decisions operationally and socially more complex.
    - Higher frequency and coupling of operational transients, requiring anticipation rather than reactive management.

- **What new organizational interfaces and coordination mechanisms are required?**
    - Multiplication of stakeholders (nuclear operators, industrial users, energy actors, regulators) → need for structured coordination frameworks to ensure coherent decision-making and a shared prioritization of safety across all actors.
    - Importance of organizational and physical proximity to ensure shared understanding and reliable coordination.
    - Limitations of remote coordination → need for robust communication and synchronization mechanisms.
    - Emergence of intermediate roles (e.g., supervisors) acting as mediators between competing objectives → need for reshaping team composition and responsibility allocation.

- **How can control room design and procedures support safe operation?**
    - Need to keep operators "in the loop" despite increasing automation.
    - Systems must support anticipation of transients, not only post-event response.
    - Importance of providing visibility (direct or mediated) of downstream uses to enhance understanding and vigilance.
    - Interfaces should enable an integrated representation of system interactions (electricity, heat, industrial uses).
    - Adaptation to multi-unit supervision → tools for managing multiple interconnected systems.

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The findings regarding multi-unit supervision highlight the emergent and collective nature of the “big picture.” As a result, they are less able to provide precise answers to the research questions identified in Section 8.1.

However, the process of knowledge acquisition regarding the potential effects of increased reliance on passive safety systems, multi-unit supervision, and cogeneration on human activities continues. The focus is now on integrating the knowledge gained from this research, as well as that presented in D5.1, into the design of scenarios that will be played out within a full-scale multi-unit control room simulator. These simulation sessions will provide additional insights and thus enable the presentation, at the conclusion of the EASI-SMR project scheduled for 2028, of robust and balanced research results for all three of these “innovations” that lie at the heart of WP5’s research questions.

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