EASI SMR

D5.1

Main HOF issues regarding passive safety systems in LW-SMRs

Céline PORET (ASNR)
Alexandra WARTEL (ASNR)
Robert MCDONALD (IFE)

1. Document information

Grant Agreement Number	n°101164810
Project Title	Ensuring Assessment of Safety Innovations for SMR
Project Acronym	EASI-SMR
Project Coordinator	Nicolas Sobecki, EDF
Project Duration	1 September 2024 – 31 August 2028 (48 months)
Related Work Package	WP5
Lead Organisation	ASNR
Contributing Partner(s)	Céline PORET (ASNR), Alexandra WARTEL (ASNR), Robert MCDONALD (IFE)
Submission Date	18/12/2025
Dissemination Level	Public

2. History

Date	Submitted by	Reviewed by	Version (Notes)
09/12/2025	Céline PORET	Nicolas Sobecki	11/12/2025

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by

Table of Contents

Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

List of Figures

List of Tables

Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

3. Acknowledgements

We would like to thank all the people interviewed for agreeing to share their knowledge and their feedback on passive safety systems. We would like to extend our special thanks to the Passive Plant team. By sharing their valuable practical experience with passive systems, they enable the nuclear community to acquire essential knowledge about these systems when they are integrated into a real plant. This knowledge is essential to the collective and multidisciplinary effort to understand how these systems work, with the overall goal of ensuring safety.
We would also like to thank people from VTT who incorporated questions about passive systems into their own interviews and agreed to share the data collected in this process. Finally, we would like to thank all the reviewers of this document, both from ASNR, the Passive Plant (PP) team, and the EASI-SMR project.

4. Summary

This deliverable is part of the fifth work package (WP5) composed of several tasks, which focuses on issues raised by LW-SMRs regarding Human and Organizational Factors (HOF). More specifically, it is part of task 5.1, which focuses on understanding the effects of two “innovations” brought about by SMRs on control room activities, namely multi-unit control rooms and the use of passive safety systems. This report focuses on passive safety systems (PSS).

Based on research in the field of Human Factors & Ergonomics (HFE), specifically French-speaking ergonomics, this report offers an insightful perspective on passive safety systems based on their relationship with human actions and activities.

The methodology combines interviews with a literature review on the topic of PSS, particularly Thermal-Hydraulic (T-H) passive systems based on natural circulation on which we chose to focus the research. It develops two complementary analytical approaches: 1) Identify the specific features of passive systems from a technical perspective to identify their potential effects on human activities (outside of any real plant) and 2) Identify the effects of these systems on human activities based on operating experience data from a real plant incorporating these T-H systems.

The results vary at different levels.

Some results highlight certain potential effects of passive systems on human actions and activities, which may ultimately have an impact on safety. In this regard, the main results show that, while control room operators will always need to understand what the system is doing (and in this respect T-H passive systems are no different from automated systems), T-H passive systems introduce a specific feature: their potential oscillatory nature and intermediate operation can make it difficult for operators to diagnose the effectiveness of the system. Another finding concerns the potential exacerbation of the importance of maintenance activities introduced by T-H passive systems, and thus a simplistic link should not be drawn too quickly between the reduction in the number of components requiring maintenance, made possible by the integration of passive systems, and the simplification of maintenance activities. Finally, another finding shows that passive safety systems could be sensitive to inadvertent actuation, which could lead to additional recovery activities intended to restart the plant. These additional activities should not be underestimated in the context of SMR development, where the aim is to reduce the number of operators in the control room while monitoring multiple reactors.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Other results are more specifically intended for the Human Factors & Ergonomics community and offer an understanding of T-H passive systems that could be useful for this community.

This research report is the first step in a process of knowledge acquisition that will continue throughout the EASI-SMR project. It will be followed by experiments in IFE's multi-unit control room simulator, including scenarios which incorporate some of these systems.

5. Keywords

Passive safety systems, Human Factors and Ergonomics, human activities, SMRs.

6.Abbreviations and acronyms

Acronym	Description
AC	Alternating current
C&D	Communication & Dissemination
CWC	Cold Wall Condenser
ECCS	Emergency Core Cooling System
HFE	Human Factors and Ergonomics
HOF	Human and Organizational Factors
IFE	Institute for Energy Technology
LW (SMR)	Light Water (SMR)
NC	Natural Circulation
PP	Passive Plant
PSA	Probabilistic Safety Assessment
PSS	Passive Safety Systems
RCIC	Reactor Core Isolation Cooling system
RCS	Reactor Coolant System
SACO	SAfety COndenser
SMR	Small Modular Reactor
T-H	Thermal-Hydraulics or Thermal-Hydraulic
WP	Work Package

Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

7. Introduction

This deliverable is part of the fifth work package (WP5) composed of several tasks, which focuses on issues raised by LW-SMRs regarding Human and Organizational Factors (HOF). More specifically, it is part of task 5.1, which focuses on understanding the effects of two “innovations” brought about by SMRs on control room activities, namely multi-unit control rooms and the use of passive safety systems. This report focuses on passive safety systems[1] and is the first step in a process of knowledge acquisition that will continue throughout the EASI-SMR project. This deliverable is exploratory and intended to identify the potential HOF issues posed by passive systems and will be followed by experiments in IFE's multi-unit control room simulator, including scenarios which incorporate some of these systems.

This report problematizes the question of the potential effects of passive safety systems on human activities from an anchoring in Human Factors & Ergonomics (HFE), more peculiarly in French-speaking ergonomics. After presenting this conceptual framework (Parts 8 & 9), we argue our focus on T-H passive systems which correspond to the systems brought back into visibility by the development of LW-SMRs (part 10). We then present the results of this exploratory research in parts 11 and 12.

8. Why are Human Factors & Ergonomics (HFE) interested in Passive Safety Systems?

As indicated in the introduction, this deliverable is part of WP5 which focuses on issues raised by LW-SMRs regarding HOF. From a disciplinary point of view, it therefore falls within the field of HFE. We present this discipline in 8.1 before further clarifying the reasons why passive safety systems are of interest to it. In 8.2, we indicate that passive safety systems immediately raise questions for HFE because one of the key issues at the heart of their design is the no-need of human actions. "Human action" is defined here as any operating action performed by an operator in the control room or in the field, for a given period after an accident[2]. Once it appears that these actions can be excluded, HFE comes into play and seeks to investigate whether this exclusion is real and whether it can have harmful effects on the control of nuclear and radiological risks. In 8.3, we specify that passive systems also raise questions for HFE because, as the activation of passive safety systems can lead to a set of operating actions which are executed and linked together without the intervention of the operator, they appear to be like automated or even autonomous systems[3]. We may therefore ask ourselves whether the design and evaluation principles developed by HFE for these systems—namely, the principles of transparency and explainability[4]—should be applied in the same way, or whether the passivity of the systems introduces differences.

---

[1] Another report, D5.3, will focus on multi-unit control rooms and will be published in the first half of 2026.

[2] For example, for the Westinghouse AP1000 reactor, which is one of the first models offering this enlarge use of passive safety concept, no operator action is required for 72 hours after an accident.

[3] We clarify the definitions of these systems in part 8.3.

[4] We clarify the definitions of these principles in part 8.3.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

8.1. What are Human Factors & Ergonomics (HFE)?

Human Factors & Ergonomics is « *the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance. […] HFE uses a holistic, systems approach to apply theory, principles, and data from many relevant disciplines to the design and evaluation of tasks, jobs, products, environments, and systems. HFE takes into account physical, cognitive, sociotechnical, organizational, environmental and other relevant factors, as well as the complex interactions between the human and other humans, the environment, tools, products, equipment, and technology"* (IEA website, What Is Ergonomics (HFE)? | International Ergonomics Association).

In other words, it is a scientific discipline that is itself founded at the crossroads of several disciplines concerned with humans (psychology, ergonomics, sociology, *etc.*). The objective of HFE is to develop an anthropocentric approach to diverse complex sociotechnical systems to improve at the same time human well-being and the performance of overall systems. Nuclear safety constitutes one dimension of this overall performance of systems. Three characteristics form the basis of HFE and characterize it intrinsically (Dul, Bruder, Buckle, Carayon, Falzon, Marras, Wilson & Van der Doelen., 2012). HFE:

- **takes a system approach**: HFE studies, evaluates and designs complex systems of variable granularity, ranging from *"a single individual using a hand tool or as complex as a multinational organization"* (Hendrick & Kleiner, 2002, p. 1).
  HFE attributes several essential characteristics to the complex systems it studies (Wilson, 2014), including:
  - consideration of the *context* that gives rise to complexity and which argues in favour of studies "in the field", in the real situation, rather than in the laboratory which has the effect of reducing this complexity;
  - a permanent articulation between the understanding of the *interactions* that underpin this complexity and the system considered *holistically*. This involves starting from the interactions between different elements of the system to access phenomena at another level that emerge from these interactions and which, in turn, can have effects on each part of the system taken in isolation;
  - consideration of the *emergent* dimension of the system's properties, from circumstances and events even if there are also generic dimensions

  Integrating these different characteristics (context, interactions, holism, emergence), Wilson (2014) defines the systemic approach developed by HFE as: *"Understanding the interactions between people and all other elements within a system, and design in light of this understanding, a system being a set of inter-related or coupled activities or entities (hardware, software, buildings, spaces, communities and people) with a joint purpose; [HFE] seeks to understand the links between the entities may be of state, form, function and causation; [HFE] conceptualises any system of interest as existing within a boundary and thus a defined context, having inputs and outputs which may connect in many to many mappings; [HFE] treats the system as holistic with the whole usually greater (more useful, powerful, functional etc.) than the sum of its parts; and [HFE] explicitly recognizes that the system changes and modifies its state and the inter-actions within it in the light of circumstances and events, thus showing emergent properties"* (p. 12).

- **is design-driven**: HFE is not limited to understanding and evaluating systems; it also aims at their transformation and develops a design approach. Within this framework, HFE has developed generic design criteria for specific interaction meshes. For example, the transparency criterion (Skraaning & Jamieson, 2021; Saghafian et al., 2025) concerns the

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

design of the *interactions between human actors and automated systems*, and postulates that human actors must be kept informed of what the automated system is doing, so as to always be able to understand what is happening and what should be implemented in the event of automation failure. On a broader scale, Poret & al (2016) proposed the continuity criterion for the design of organizations and *interactions between human actors in contexts of multiple distribution (their activities are distributed in time, space, and potentially different cultures)* where overall performance is targeted. This criterion postulates that continuity between these multi-distributed activities has positive effects on the overall performance of the system and that this need for continuity must therefore be integrated into the design of organizations and the technical systems that support them.

- **focuses on two related outcomes**: In its design and transformation approach, HFE pursues two concurrent objectives: to improve both the well-being of the people involved in the system, as well as the overall performance of the system.

It is important to emphasize that, if this definition and these general characteristics are shared internationally by members of the HFE community, different ways of articulating disciplines and theoretical frameworks coexist in HFE, which can sometimes seem disconcerting to those outside the HFE community. This diversity is fundamental to the dynamism and richness of HFE, provided that it is made explicit. In this context, we will detail our own theoretical approach, which forms the conceptual basis of this report, in section 9.

8.2. HFE Design assumptions of passive safety systems seem to exclude human actions: a concern to HFE

At first glance, it may seem surprising to some that HFE is interested in passive safety systems, given that one of the characteristics frequently highlighted about these systems is that they enable operator actions to be "eliminated," the approach being to *"eliminate operator action rather than automate it"* (Abram & Elshahat, 2012, p. 59). For example, in the Westinghouse AP1000 power plant model, which is one of the first reactors to incorporate extensively a passive safety concept, it is emphasized that *"the passive safety systems require no operator actions to mitigate design basis accidents"* (Abram & Elshahat, 2012, p. 60). Less reliance on operator actions – at least in short or medium term - was one of the two challenges that led to this new design (Matzie, 2008, p. 1856), which began in 1985 with the initial conceptual design of a smaller version, the AP600. The design philosophy behind passive systems can be summarized as *"passive systems can compensate for erroneous or inadvertent detrimental (deliberate or less) operator actions or mitigate their consequences"* (OECD-NEA, 2024, p. 196). In other words, passive systems have the potential to "eliminate" (or delay) the need of operator actions,[5] and they are of interest to the nuclear industry, notably for this reason. It is interesting to note here a common idea between these passive systems and automated/autonomous systems, which, in most cases, *"carry (at least implicitly) the idea that the 'human factor' is primarily a source of errors or problems"*[6] (Compan, Brunet, Mestanza, Renonciat, Monéger, Récopé, Rix-Lièvre & Coutarel, 2023, p.4).

Furthermore *"[...] passive [safety] has a connotation of superior performance"*[7] (IAEA, 1991, p. 15). This context, combining a desire to "eliminate" operator actions and a consideration of inherently more reliable systems, may, in our view, lead to less consideration being given to human actions

---

[5] As specified in 8, this elimination concerns any operating action performed by an operator in the control room or in the field, for a given period after an accident.

[6] The quote was translated from an article published in French by the authors of this report.

[7] IAEA reports this to moderate and emphasize that this assumption "cannot be accepted without evaluation and justification" (AIEA, 1991, p. 15).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

and activities during the design phase. This risk has also been highlighted by authors working in the field of French-speaking ergonomics who are interested in human activities in the context of autonomous system design. They specify that *“thinking about design in terms of autonomy leads to many issues relating to human activity and work being relegated to later stages of the design process. This has consequences for project performance, and more specifically for the quality of the work itself”*[8] (Compan & al, 2023, p.2). This could, for example, lead to *“out of the loop performance problems”*[9] or other problems that may cause complications in the performance of human activities once the systems have been designed. Thus, as mentioned by the OECD-NEA (2024, p. 218): *“Although the performance of passive systems does not rely on operator actions, human actions should be carefully considered when assessing passive systems.»*. More generally, the fact that operators take no action during the passive safety system’s actuation and operation can *"impose additional demands on human performance during the operation of the facility as a whole. With this in mind, a proper human factor design of the [passive system] is even more important than for active systems”*[10] (OECD-NEA, 2024, p. 260-261). The present research is part of this effort to understand the potential effects of passive safety systems on human activities during control or mitigation of accidents and, ultimately, on nuclear safety.

8.3. Passive systems, automated systems, autonomous systems: synonyms from an HFE perspective?

As said previously, because the actuation of passive safety systems can lead to a set of operating actions which are executed and linked together without the intervention of the operator, they appear to be like automated or even autonomous systems[11]. So, another reason to take an interest in passive safety systems for HFE lies in their apparent similarities with automated and autonomous systems, considered significantly by HFE. It is therefore important to investigate whether the HFE criteria for designing and evaluating such automated and autonomous

---

[8] The quote was translated from an article published in French by the authors of this report.

[9] *“The out of the loop performance problem arises when operators suffer from complacency and vigilance decrement; consequently, when automation does not behave as expected, understanding the system or taking back manual control may be difficult”* (Gouraud, Delorme, Berberian, 2017).

[10] *« It can be reasonably stated that the actuation and long-term operation of a passive system can be less demanding, in terms of human actions, than an equivalent active system. At the same time, if passive systems behave unexpectedly, it is much more demanding to control their behaviour. Operator actions are possible when a function is lost during the operation of an active system: e.g. an alternative electricity source can be activated and valves can be opened and closed to restore the operation of a pump; a standby, redundant pump can be put in operation. Any operator action is more difficult or even impossible when passive systems are concerned: e.g. if large pressure drops (higher than predicted at the design level) occur during core reflow and prevent gravity flooding (of the core), the operators take no action. Furthermore, the presence of, and reliance on, passive systems may impose additional demands on human performance during the operation of the facility as a whole. With this in mind, a proper human factor design of the [passive system] is even more important than for active systems”* (OECD-NEA, 2024, p.260-261).

[11] A generally accepted definition of automation is *“a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator”* (Parasuraman, Sheridan & Wickens, 2000, p.287). Autonomy is defined as *“the extent to which a system can carry out its own processes and operations without external control”* (Beer, Fisk & Rogers, 2014, p.77). Although these two types of systems are similar in that they perform a set of functions, tasks, and processes on their own without human intervention, they differ in that *“automated systems operate on predefined instructions, performing tasks within set boundaries, while autonomous systems dynamically adapt and learn, evolving with their environments”* (Myklebust, Stålhane & Vatn, 2025, p.115).

Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

systems, namely transparency[12] and explainability[13], also apply to passive systems, or whether the passivity of these systems introduces particularities that could give rise to new needs for the performance of human actions and may therefore lead HFE to adapt its own design and evaluation criteria.

This investigation is even more important given that there is virtually no HFE literature about passive safety systems, unlike the extensive literature that exists on automated and autonomous systems. However, as early as 2002, the OECD-NEA called on Human factors experts, emphasizing that *"There is a need to clearly identify the role of the operator in systems that are fully passive, contain an initiating active component, or have a combination of active and passive components. This is an area where human factors experts could provide help"* (2002, p.10). This research follows on from this observation by the OECD-NEA and seeks to identify the role of operators in systems that are more or less passive, as well as how these different roles should be supported[14].

9. An exploratory research in French-speaking ergonomics on passive safety systems

9.1. From HFE to intrinsic approaches to human activity

As indicated at the end of Part 8.1, different ways of articulating disciplines and theoretical frameworks coexist in HFE.

Below, we present our theoretical foundation, illustrated in Figure 1. This foundation starts from HFE, presented in 8.1 and goes to intrinsic approaches to human activity[15], via an inclusion in French-speaking ergonomics. Each higher level of the figure considers the characteristics of the lower levels as its own.

---

[12] Automation transparency is *"a long-held human factors design principle espousing that the responsibilities, capabilities, goals, activities, and/or effects of automation should be directly observable in the human-system interface"* (Skraaning & Jamieson, 2021).

[13] The principle of explainability is similar to that of transparency, with the exception that it only concerns autonomous systems: *"it consistently refers to explaining what the intelligent agent is doing"* (Karran et al., 2022, cited by Saghafian et al., 2025).

[14] It is important to emphasize here that this subsection presents the problematization of the deliverable in the field of HFE. The aim is to identify whether the passivity of systems is causing changes in their interaction with operators and, therefore, whether this passivity calls for a change in the design and evaluation criteria for automated and autonomous systems that have been developed by HFE regarding this interaction. In no way is the idea here to suggest that passive systems are responsible for operators playing a less important role in the event of an accident, given that it is generally expected that control of accident relies on limited human actions whatever the design is. WENRA reference levels therefore require for control of design basis accidents that *"activations and control of the safety functions shall be automated or accomplished by passive means such that operator action is not necessary within 30 minutes of the initiating event"* (WENRA, 2021, p. 18).

[15] We think it is important to emphasize again here that the word "activity" is used in this section according to its conceptual meaning in French-speaking ergonomics but that the scope of the current report is, at the outset "human action", defined in the nuclear community as any operating action performed by an operator in the control room or in the field, for a given period after an accident. Two important clarifications at this stage: 1) the term "action" is used here in its specific meaning in the nuclear field and not in a conceptual sense, and 2) this research has led us to broaden the initial scope, since in the rest of this report we will be addressing activities such as maintenance and not just "human actions."

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

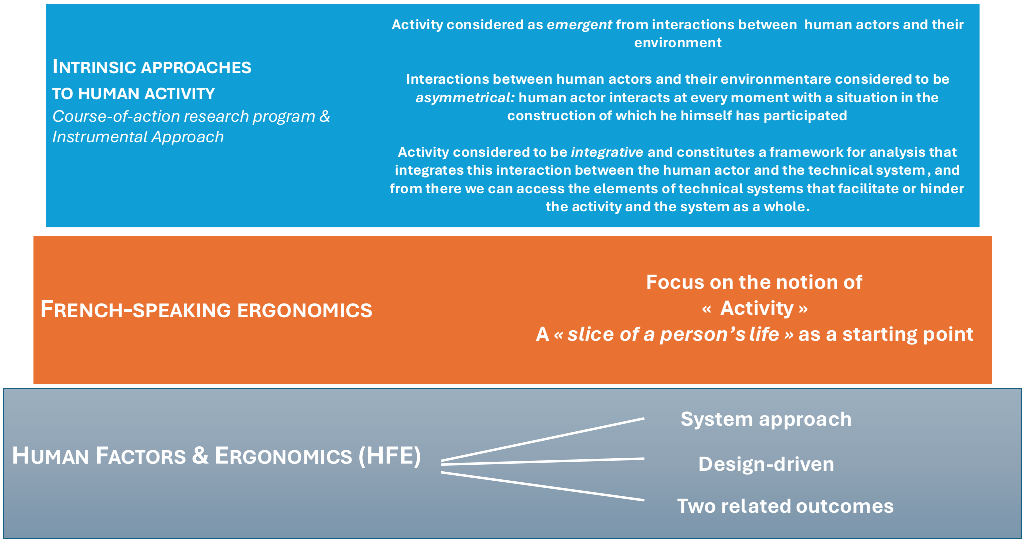

Figure 1 - Theoretical foundation of the present research

So, French-speaking ergonomics pursues the general objectives of HFE, adopting a systemic & design approach, and aiming to improve both the well-being and overall performance of the sociotechnical systems analysed. More specifically, the general concept at the heart of French-speaking ergonomics that enables it to achieve these various objectives is that of "activity". This general concept *"appears as a general framework of thought whose boundaries have evolved according to the types of problems that ergonomists have had to deal with due to technological and social changes, the new fields that the methodological developments have opened up and inter-disciplinary discussions"* (Daniellou, 2005, p. 417). Put simply, we can define activity, following Daniellou (2005), as *"a slice of a person's life whose observed motivations are not all found in the work situation"* (p. 416).

To analyse this *"slide of a person's life"*, several epistemological and theoretical communities coexist within French-speaking ergonomics. As far as we are concerned[16], we subscribe to a constructivist paradigm and define the activity at the articulation of two theoretical approaches developed within the framework of French-speaking ergonomics; it is the *"course of action research program"* (Poizat & Martin, 2020) and the *"instrumental approach"* (Rabardel & Béguin, 2005). These two theoretical approaches are "intrinsic" approaches to human activity, they seek *"to understand 'from within' how the human actor constructs his/her activity to attain the object given the resources and constraints at his/her disposal"* (Daniellou & Rabardel, 2005, p. 356), to *"apprehend reality from the same angle as the [human actor], and to understand the activity generating mechanisms on these grounds"* (Rabardel & Béguin, 2005, p. 431).

Within these intrinsic approaches, activity is considered as *emergent* from interactions between human actors and their environment, and always *"open at both ends"* meaning that *"no portion of human activity contains its intelligibility within itself" and that "every portion of human activity maintains relationships with past and future portions"* (Theureau, 2006, pp. 47-48). From a methodological point of view, this means that we attach importance to the activity that emerges at every moment "here and now" from the interactions between the actor and his/her environment, while having methodologies to access the past and projective dimensions of this portion of activity, and to access generic aspects of activities beyond very specific aspects related to a particular person.

---

[16] This concerns more precisely the epistemological and theoretical rooting of ASNR within WP5.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by

In line with this way of considering activity, interactions between human actors and their environment are considered to be *asymmetrical*, that is to say that the human actor interacts at every moment with a situation in the construction of which he himself/she herself has participated. In terms of interactions with technical systems, this means that the human actor and the technical system are not interacting cognitive systems, but rather that it is the human actor who gives meaning to the system by integrating it into his/her activity. In other words, we seek to understand technical systems from the perspective of the human actor and his/her activity.

Finally, the activity is considered to be *integrative*, in the sense that it:

- integrates both past and future dimensions that extend beyond the here and now;
- integrates collective dimensions that extend beyond individual ones and reach toward higher levels of systemic understanding;
- synthesizes a set of determinants and components of the system, including technical systems.

Thus conceptualized, activity constitutes a relevant entry point for accessing complexity. If we decide to reduce the mesh of the system studied to the interaction between human actors and technical systems[17], the activity constitutes an entry point allowing us to identify the way in which these technical systems are integrated into this activity, and thus the way in which they influence/hinder it, and ultimately the effects of these influences on the overall performance of the sociotechnical system. In other words, applied to the present research, entering through the activity in the control room would allow us to access the way in which this activity has integrated the passive safety systems, and the effects of the latter on the conditions of realization of this activity and, ultimately by going up the levels, to identify potential effects on the overall performance of the sociotechnical system – namely nuclear safety.

9.2. Intrinsic approaches studies phenomena from and for the perspective of human activity

As stated above, if the activity constitutes an entry point, this assumes that the technical systems we wish to evaluate in terms of their effects on human activities are already integrated into that activity. Otherwise, rather than starting from the activity to identify the effects of these technical systems on it, we must adopt a different approach: starting from the characteristics of the technical systems to identify those that could have effects on human activities. In one case (“From”), ideally, we start with the activity, which provides an ideal framework for understanding technical systems in terms of what they enable or preclude in terms of possibilities. In another case (“For”), we start with technical systems and their specific characteristics to draw a hypothetical line to human activities.

The present research falls into the second category. For various reasons (underdeveloped systems, virtually inaccessible for observation in activities in real situations, etc.), it was not possible to start from the actual activity to understand how passive systems are integrated into it. We therefore started with these systems, seeking to identify the specific characteristics resulting from their passivity and to draw a line to human activities by seeking to identify the potential effects of these characteristics on these activities. It is in this sense that this is “exploratory” research, i.e., research that cannot be completely conclusive in the sense that the link drawn to the possible effects on human activities is based on hypotheses. However, it’s important to highlight that these hypotheses did not come out of nowhere: they are based on the researchers’ knowledge about these human activities and their needs.

To do this, it was necessary to delve into the technique. It was not a question of becoming technical experts in these systems, but rather of acquiring sufficient technical understanding

---

[17] This reduction corresponds to that made in the context of this research.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

(sometimes simplified) to identify the technical specificities which seemed to be able to have effects on human activities.

9.3. Methodology

The data collection methodology consisted of combining interviews with a literature review on the topic of passive safety systems, particularly Thermal-Hydraulic passive systems based on natural circulation.

We conducted 25 interviews with technical experts from various backgrounds[18], former operators, and operators/trainers at a nuclear power plant incorporating the passive thermal-hydraulic systems on which we chose to focus our research. It is important to emphasize that, given our definition of the activity and the objectives of the research, interviews with former and current operators had a special place. Through the interviews with them, we sought to gain insight into their control room activities involving passive safety systems and to revisit experiences with them that were significant *from their perspective* regarding passive safety systems. It was with them that we were led to clarify elements based on written exchanges after the interviews, to try to go into more detail and access contextual elements to understand precisely the significant experiences that they had shared with us.

The interviews with the experts, while allowing us to understand the role of passive systems in their own activities, did not, however, address control room activities. Therefore, these interviews were more intended to deepen our technical understanding of passive systems and the scientific context surrounding them, and to identify the specific issues posed by these systems in each of the experts' specialties. For example, we sought to understand the issues raised by passive safety systems from the point of view of Probabilistic Safety Assessment (PSA) with an expert in the field, while we sought to understand the issues and challenges of qualifying codes with researchers in thermal hydraulics.

The analysis took place in several stages. First, a thematic analysis was conducted for each interview. Then the thematic analyses were compared across all the interviews to identify recurring categories/themes. At the same time, to enhance technical understanding and generalization, this inter-interview thematic analysis was compared with the literature. On several occasions, we also called upon a former operator on a legacy plant to gradually improve our understanding and analysis by drawing on his technical expertise.

10. Passive safety systems & LW-SMRs: what are we talking about?

10.1. Definition of passive safety systems

Even though a survey conducted by the OECD-NEA (2024) shows that *“currently no unified internationally accepted and applied definition exists regarding passive safety systems”* (p. 68), passive systems are based on a general principle: that of *“[taking] advantage of natural forces or phenomena such as gravity, pressure differences or natural heat convection”* (OECD-NEA, 2024, p. 19). In other words, what is meant by *“passive”* is that the operation of the systems is based on natural physical phenomena. In this, they don't require AC electrical power to operate, unlike active systems which require this AC electrical power to operate pumps, valves, etc.

---

[18] Among these profiles were: experts in passive thermohydraulic systems, experts in probabilistic safety studies, HOF experts, general experts with a focus on certain specific SMR models, simulation experts, researchers in Thermal-Hydraulics.

An IAEA TECDOC (1991) proposed a definition of passive safety systems that describes a range of possibilities from passive to active, based on the identification of four *"categories"* corresponding to different *"levels of passivity"* of systems. These categories range from category A (no signal inputs of intelligence, no external power sources or forces, no moving mechanical parts, no moving working fluid) to category D, which *"addresses the intermediary zone between active and passive"* and concerns *"passive execution/active initiation"* (p. 17)[19]. Taking this typology into account, the IAEA TECDOC then defines a passive system as *"either a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation"*.

Although this definition may seem simple, it remains general and masks the specific characteristics of the various subsystems or components that comprise it. Anyway, as highlighted by WENRA (2018), when dealing with passive systems as a general concept, it is important to consider the main attributes of passive systems to draw attention to these attributes and consequential technical characteristics with regards to safety. In this context, *"there is no need to refine the definition, neither to dispute the "passivity" of some systems"* (p. 6)

10.2. A context of SMR development conducive to heightened interest in Thermal-Hydraulic passive systems based on natural circulation

Although passive systems are now gaining significant visibility with the development of SMRs, they are not new and are already integrated into legacy plants. As the OECD-NEA (2024, p. 22) points out, "*passive systems have been embedded in nuclear reactor technology design and safety since the beginning*". This is the case, for example, with the best-known systems[20], such as accumulators or *"pre-pressurized core flooding tanks"*, which constitute part of the Emergency Core Cooling System (ECCS), in case of LOCA transient. They inject water into the RCS when the pressure inside them drops below a preset value; their operation is therefore based on a pressure difference. This is also the case for other passive systems, as recalled in an IRSN document (2016, p.1):

- nuclear fission reaction control and shutdown rods which drop by gravity upon loss of electrical power.
- thermosiphon cooling after voluntary or accidental shutdown of reactor coolant pumps, achieved by natural circulation flow due to density differences between reactor coolant system regions with different altimetry.
- hydrogen recombiners which catalyse the recombination reaction of oxygen in the air with hydrogen released in the containment under accident conditions.

There is renewed and even heightened interest in these systems within the nuclear industry. As the OECD-NEA (2024, p.220) points out: « *Passive systems are seeing wide use in many new reactor designs and will likely play a major role in the advancement of the nuclear energy industry in the years to come*". This heightened interest can be explained, in part, by the context of SMR development, whose small scale – including reduced power -opens new design possibilities. First, this small-scale naturally lends itself to the integration of passive systems, as this simplifies the design, by reducing the number of components in the plant and reducing the use of active components such

---

[19] It is interesting to note that this categorization is not universally accepted when we ask people to define passive safety systems: *"Once you start adding pumps or other devices that force the system to operate, I don't understand why we still call it passive"* (thermal-hydraulics expert).

[20] We make this observation because, during interviews, accumulators are the passive systems that are most spontaneously mentioned or used as examples (with the exception of people with a specialized profile).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

as pumps[21]. This reduction in the number of components, which is particularly consistent with the concept of compactness that characterizes SMRs, is presented as a way to reduce construction, operational, and maintenance costs. Furthermore, this small-scale approach related to SMRs allows designers to see the integration of these passive safety systems in a new light, particularly the Thermal-Hydraulic (T-H) passive systems which rely on natural circulation[22]. As highlighted by the European PASTELS project (Montout, 2024, p.5), *« These design options for the reactors of the future are even more interesting for low-power reactors such as small modular reactors (SMR), where the energy to be extracted during an accident is lower and therefore requires the use of smaller systems, particularly from the point of view of the ultimate heat sink [and it's] easier to implement, with a lower impact on the construction of structures than with high-power reactors[23]"* (Montout, 2024, p.5). As indicated by one of the people interviewed as part of this exploratory research (T-H researcher), confirming this idea, *"Natural forces are weak per meter of height, so to achieve a very good circulation effect, you need very large systems, which makes them expensive and complicated to design. The SMR is smaller in scale, so [...] it becomes super-efficient."*

So, the small size of SMRs is often claimed as easing the possibility of considering T-H passive systems as capable of fully ensuring certain safety functions, particularly those related to core decay heat removal, containment cooling and pressure suppression[24]. In other words, what is new with SMRs is not the integration of T-H passive systems, given that, in legacy plants, this natural convection phenomena exist during certain transient phases. What is new with SMRs is that they could be seen as able to provide "by nature" the opportunity to fulfill a safety function in an entirely passive manner by relying on these systems[25], while in legacy plants the safety function integrates but generally does not rely primarily on this kind of systems. This is where the relative "novelty" of SMRs lies when it comes to passive safety systems and one of the reasons[26] why we chose to focus this exploratory research on these T-H passive systems.

10.2.1. General presentation of the T-H passive systems based on natural circulation

The T-H passive systems transport heat from point A to point B using a driving force based on natural phenomena, in particular the effects of gravity and rely on natural circulation. Natural circulation (NC) is defined as involving *« the use of gravity force for transferring thermal power from an assigned heat source to an assigned heat sink"* (D'Auria, 2018, p.12), or as the *"complex set of thermohydraulic phenomena that occur in a gravity environment when geometrically or materially*

---

[21] Even though it is not an SMR, the Westinghouse AP1000 reactor is an interesting example to illustrate this reduction in components. Compared to older reactor designs, the Westinghouse AP1000 incorporates *"60 percent fewer valves, 75 percent less piping, 80 percent less control cable, 35 percent fewer pumps, and 50 percent less seismic building volume"* (Abram & Elshahat, 2012, p. 50).

[22] In the remainder of this document, we will refer to these systems as "T-H passive systems". We provide a definition of these T-H passive systems in the following section (10.2.1).

[23] Even though, of course, they do exist in high-power reactors such as Westinghouse's AP1000 and other models.

[24] Given the simplification challenges mentioned above, this change in the way T-H passive systems are considered and valued in safety demonstrations is the reason why many components that were considered safety-related in older plants have been reclassified as non-safety-related. This leads to *"great simplifications in procurement, construction, startup, and operation including inservice inspection/testing and maintenance"* (Schulz, 2006, p. 1553).

[25] This innovation promoted by SMRs is already incorporated into nuclear power plants such as the Westinghouse AP1000, which features an innovative passive safety concept. However, this concept seems rather isolated in relation to the current fleet of nuclear power plants, unlike SMR models, which offer this passive safety concept based on passive safety systems in a significant way.

[26] Several other reasons confirmed this choice: because these systems are also the ones that still seem to raise the most questions today in terms of their reliability and safety demonstration and for which we have the least operating experience.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

distinct heat sinks and heat sources are connected by a fluid" (IAEA, 2012, p.9). More precisely, *"the heat sink is normally positioned higher in relation to the heat source to facilitate the movement of the working fluid aided by density gradients and gravity during the upward and downward flows, respectively"* (OECD-NEA, 2024, p. 47).
Two types of systems fall into this category (IAEA, 2009): those aimed at removing decay heat from the core (Safety Condenser or "SACO", Isolation Condenser, Passive residual heat removal heat exchangers, *etc.*) and those aimed at cooling the containment building and relieving pressure (Cold Wall Condenser, *etc.*)[27].

10.2.2. A particular link to reality that challenges all disciplines seeking to acquire knowledge about how these T-H passive systems operate

This paragraph presents how, through examples drawn from literature, the design of passive systems calls into question certain tools (codes, PSA models) that aim to demonstrate their reliability. In this part of this report we don't take position but address the issues within the scientific community. In this section we focus on the two PSS types mentioned above (§10.2.1).
The positioning of passive T-H passive systems to perform safety functions exacerbates the need to evaluate and demonstrate differently their reliability, defined as *"the probability to perform the requested mission to achieve the generic safety function"* (Burgazzi, 2007, p. 672). However, the phenomenal dimension of these systems opens specific needs for demonstrating this reliability, as it is now a question of demonstrating not only material reliability, but also the reliability of the natural process itself. This reliability of the process itself is supported by the concept of *"functional reliability/failure"*, which is the ability of a passive system to perform its mission under given conditions and is thus closely linked to the scenario and to the initial design of the installation: *"[…] a passive safety system may not be capable of performing its assigned function, even in the absence of mechanical or electrical failure. Indeed, as mentioned earlier, a passive safety system may rely on low-intensity phenomena (e.g. natural convection) which, under certain conditions, may be insufficient to perform its function. Such failure may occur when the phenomena at play are sensitive to system geometry (e.g. head loss sensitivity), ambient parameters and mismatches between design expectations and actual conditions. This type of failure, referred to as a functional failure, may lead to non-actuation or shutdown of a passive safety system, or unexpected operating conditions"* (IRSN, 2016, p. 5). In our opinion, the OECD-NEA (2024) summarizes well how the phenomenal characteristics of passive T-H systems impact the possibility of assessing their reliability: *"[…] the weak driving forces of passive systems (considering gravity draining for makeup water or natural circulation for thermal power releases) make it more difficult to assess (and thus demonstrate) their reliability due to their sensitivity to multiple parameters, e.g reactor state, influence of external disturbances, etc. Validation and qualification of simulation codes, used in the safety case, are much more complex, with multiple experimental programme developments, for separate effect characterization, integral test demonstration and qualification. It is a key challenge for safety architecture based on passive systems to ensure that all reactor configurations in all major transients are correctly reproduces in the integral test programmes, on the right scale, with good reproduction in the simulation codes"* (p. 221).

At the same time, the phenomenal scale of TH passive systems makes their effectiveness dependent on the actual conditions in which this phenomenon occurs. This poses challenges for anyone wishing to draw conclusions about the reliability of the phenomenon (PSA models, code qualification, *etc.*), as the actual reliability of the phenomenon requires understanding it in relation to reality. This has led to numerous studies on code qualification to simulate these phenomena and the evolution of PSA models.

---

[27] For a more detailed technical presentation of these systems, see the OECD-NEA report (2024) or IAEA-TECDOC-1624 (2009).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

For example, for Probabilistic Safety Assessment (PSA) models, the demonstration of the physical phenomena reliability involves the *"evaluation of the thermal-hydraulic unreliability to be accounted for in the probabilistic safety analysis studies"* (Burgazzi, in OECD-NEA, 2002, p.106) and thus *"merging probabilistic models with T-H models, i.e., dynamic reliability [...] to accomplish the evaluation process of T-H passive systems in a consistent manner"* (Burgazzi, 2007, p. 675). On this subject, IRSN (2016) highlights that *"it is important to consider the difficulty in producing conclusive probabilistic safety assessments (PSAs), in particular due to the difficulty of assigning failure probabilities to passive safety systems under all conditions covered by PSAs, and the lack of operational feedback on the reliability of such systems under accident conditions" (p.5)*. This scarcity of operational and experimental data is the origin of the integration of many uncertainties in attempts to approach the reliability of the phenomenon[28]: *"Innovative passive systems for advanced reactors often consist of equipment with very limited operating experience. Consequently, one needs to deal with a lack of reliability figure and the resulting data uncertainties. As a consequences generic data, theoretical data assessment or data assessment by engineering judgement have been applied to failures mode of passive equipment. This induces larger epistemic uncertainties of the unavailability data for passive equipment compared to active equipment"* (OECD-NEA, 2024, p.205).

In a 2024 report, the OECD-NEA (2024, p.200) notes that from this PSA perspective, *"studies for existing and innovative nuclear reactors (and related designs), the general practice at the time the report was developed, is to consider only component failure probabilities when addressing the reliability of passive systems (either in deterministic or probabilistic studies), disregarding the T-H physical phenomena on which the system is based such as the natural circulation. Then, the functional failure is not taken into account [...]. The key issues to be addressed are thus how to quantify the functional failure in the passive system reliability and how to integrate passive system reliability in a PSA study"*. So, these issues are topical and are still the subject of debate within the scientific community[29].

11. Specific features introduced by the passivity of the T-H passive safety systems that may have an impact on human activities

This section presents the characteristics of passive safety systems relying on natural circulation that emerge from the analysis of interviews with experts from different fields. In other words, these are generic results related to this type of T-H passive systems "in essence," i.e., not considered in the context of a specific installation.

11.1. Systems that rely on smaller driving forces: operation marked by potential instabilities,

---

[28] Burgazzi (2012) distinguishes *"two facets to this uncertainty, i.e., "aleatory" and "epistemic" that, because of their natures, must be treated differently. The aleatory uncertainty is that addressed when the phenomena or events being modelled are characterized as occurring in a "random" or "stochastic" manner and probabilistic models are adopted to describe their occurrences. The epistemic uncertainty is that associated with the analyst's confidence in the prediction of the PSA model itself, and it reflects the analyst's assessment of how well the PSA model represents the actual system to be modelled. This has also been referred to as state-of-knowledge uncertainty, which is suitable to reduction as opposed to the aleatory which is, by its nature, irreducible. The uncertainties concerned with the reliability of passive system are both stochastic, because of the randomness of phenomena occurrence, and of epistemic nature, i.e. related to the state of knowledge about the phenomena, because of the lack of significant operational and experimental data"* (p. 47).

[29] One of the work packages of the EASI-SMR project directly addresses these issues (WP4).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

greater sensitivity to parameter variations, intermediate modes and slowness

The essential characteristic of these systems, from which several other characteristics derive, is that they operate using low driving forces. In T-H passive systems for core decay heat removal, for example, the circulation of fluid and therefore heat is not forced, *i.e.*, it does not rely on the use of pumps but on natural phenomena (e.g. buoyancy driven flow). These phenomena may therefore *"be vulnerable to interruption (e.g. the presence of non-condensable gases) posing a risk of instability"* (OECD-NEA, 2024, p. 83). Moreover, due to this low intensity of the natural forces at play, "*a passive safety system's performance characteristics may be particularly sensitive to ambient conditions (e.g., containment temperature increase caused by initiating event) or external hazards (climatic, seismic, etc.)"* (IRSN, 2016, p.3).

This can result in operation that is not characterized by an on/off switch but by a possible range of operation depending on different parameters: "*It's not 0 or 1, it's not like active systems where 0 or 1 means the pump starts or doesn't start. A passive system, depending on the conditions in which it starts operating, can run between 0.1 and 150%, so the question that arises is 'what are the consequences?" (T-H system expert).* This feature means that there may exist conditions in which the fluid circulation will oscillate to a greater or lesser extent, and this oscillatory operation can be more or less pronounced depending on whether it is monophasic or diphasic: "*As soon as you put liquid and steam together and try to make them work, it's clear that you can quickly encounter surprises [...] With SACO [Safety condenser], because there is a liquid- steam mixing, there are instabilities and pressure losses that we don't fully understand. There is a whole range of possible operating variations that are difficult to grasp."* (T-H passive systems expert). In other words, *"intermediate modes of operation of the system or equivalently the degraded performance of the system (up to the failure point) is possible. This gives credit for a passive system that 'partially works' and has failed for its intended function but provides some operation"* (Burgazzi, 2012, p. 51).

Moreover, another characteristic is their potential slowness. Several experts point to this slowness as being intrinsic to natural convection phenomena in certain conditions. A former operator at a legacy plant, sharing his experience of "thermosiphon cooling," confirms this assertion: "*If you lose the reactor coolant pumps before you get natural circulation going, it takes time. And when you gotta go in the response, this is way slower than if you have forced flow*" (former operator on a legacy plant). It should be noticed that this kind of behaviour is not to be generalized and is generally related to some operating conditions. Other experience feedback show a quite "violent" action of some passive systems in some other conditions due to their sizing.

11.2. TH-system testability : a matter of debate

Another distinctive feature of these systems is the difficulty to demonstrate the representativeness of the routine or periodic test. This difficulty stems from several characteristics of these systems:

- their **phenomenal or process-oriented nature**, that is to say the fact that they rely on a natural phenomenon that unfolds over a certain period of time: *"With their dependence on physical processes, passive safety systems are not amenable to routine testing as are active systems. There is not anything to test, e.g., no pumps to start. Some passive systems use valves but even operating them does not test the process because the condition that would initiate the process does not exist"* (O'Hara, et al., 2010, p. 9-10);
- their **dependence on the actual conditions under which the phenomenon occurs**: for example, these "actual conditions" are, among many other factors, those that arise from the interaction between active and passive systems or among passive systems. Indeed,

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

these systems "*rather adjust their performance to the thermal-hydraulic conditions they are exposed to [...] Consequently, the performance of a passive system may be influenced by another passive or active system*" (OECD-NEA, 2024, p. 149). This relationship between their dependence on real operating conditions and their testability is also underlined by one of the experts interviewed: *"It is difficult to test, and the same applies to periodic tests. A periodic test does not necessarily guarantee that the system will function perfectly as expected in an incident situation"* (T-H passive systems expert).

11.3. A design principle that could make T-H passive systems more prone to inadvertent actuations

Another specific feature of the T-H passive systems is based on one of the underlying design principles, namely that they must actuate in the event of a loss of AC power. The practical application of this principle in the design of the systems is that many of the valves that make them up are "fail-safe", meaning that they are designed to be in the closed position under normal conditions and to open in the event of a loss of AC power. This is the case, for example, for Westinghouse AP1000, where the valves on the PRHR-HX outlet line are fail-air operated valves, as are the CMT discharge valves to the vessel (Freis, Haspel & Tietsch, 2009).

While this "fail-safe" principle is already present in legacy plants, it is even more important in T-H passive systems because it applies more broadly and concerns valves that play an important role in triggering certain T-H passive systems. Thus, any failure in the power supply to these valves could cause the T-H passive system and the associated safety function to be activated inadvertently. This happened, for example, in Westinghouse AP1000, where "a loss of power to a passive residual heat removal (PRHR) heat exchanger (HX) outlet flow control valve (FCV) air-operated solenoid," due to "a premature fuse failure," caused a PRHR actuation (Licensee Event Report 2024-003-00). In this regard, the Licensee Event Report (LER 2024-003-00) specifies that "Design changes are in development to eliminate the potential for a single fuse failure to open the PRHR HX outlet FCV and planned for implementation during future outages" (Page 2 of 2).

Although this example concerns a specific design, it allows us to highlight an important idea that could apply to any design incorporating passive systems to ensure safety functions. Indeed, any valve that plays an important role in triggering passive systems, if it is fail-safe, must be given special attention in terms of intrinsic reliability, as well as the design of its power supply circuits. In fact, any event that would cause the valve to lose power, whether due to human error or a malfunction in the component's power supply, could cause the passive system to activate in conditions where it is not required.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

12. Effects of T-H passive safety systems on human activities

12.1. Effects identified from interviews with experts, outside of any real plant

The Table 1 provides a comparative overview of the specific features introduced by the passivity of T-H passive systems, along with their potential effects on human activities[30] (T-H system performance assessment, maintenance and training). We then discuss each point in more detail in the subsequent sections (12.1.1; 12.1.2; 12.1.3, 12.1.4).

Specific features introduced by the passivity of the T-H passive systems	Potential effects on human activities	
	In the control room	In the field/maintenance activities
Systems that rely on smaller driving forces: operation marked by potential instabilities, greater sensitivity to parameter variations, intermediate modes and slowness **(11.1)**	Assessing the effectiveness or performance of the system may be difficult, in a context where it will be virtually impossible for the operator to do action ***(12.1.1)***	A potential increase in the importance of maintenance activities and rethink of maintenance strategy ***(12.1.2)***
TH-system testability : a matter of debate **(11.2)**	A potential increase in the importance of operator training ***(12.1.3)***	
A design principle that could make T-H passive systems more prone to inadvertent actuations **(11.3)**	A potential additional workload in the event of inadvertent actuation of passive T-H systems ***(12.1.4)***	

Table 1 - From specific technical features of T-H passive systems to their potential effects on human activities

12.1.1. Assessing the effectiveness or performance of the system may be difficult, in a context where it will be virtually impossible for the operator to do action

As indicated in part 11.1, one of the specific characteristics of some T-H passive systems that arises from their reliance on smaller driving forces is that they can exhibit "intermediate" and "oscillatory" operation. This can make it difficult for control room operators to diagnose the system's effectiveness. This was highlighted by several experts interviewed: "*What is the probability that [the passive system] will work in ranges that are not quite nominal, and associated with that, what will the operator think when they can't do anything but see that things are not working quite as expected?*" (T-H passive systems expert), or "*if these [flow] oscillations result in pressure and*

---

[30] It should be highlighted that the scope of activities has been enlarged regarding the scope of human actions initially stated and defined in chapter 8. Some aspects related to maintenance have been added as they are of particular interest for passive systems even if they are not directly linked to the notion exposed above (limited of human action in short- and medium-term during accident).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

temperature oscillations at the sensors, I don't know how an operator who sees his temperature doing this [up/down movement with his hands] will react" (T-H passive systems expert).

In addition, these difficulties can be exacerbated by the fact that the system may operate slowly and that it's complex for the operator to take action to modify adequately the speed of system performance.

From a design perspective, which is one of the intrinsic dimensions of HFE and French-speaking ergonomics within which this research is conducted, the aim is to help the operator diagnose the effectiveness of the system, in addition to identifying the essential parameters to be reported to the control room for this purpose. It is important to emphasize that, even if all the parameters needed to diagnose the effectiveness of the passive system were integrated into the control room, the potentially slow and oscillatory intermediate operation of the passive system could be detrimental to the operator's understanding, but this is a result of the passivity of the system and, as such, it would be very difficult to adequately remedy it. In other words, while the criterion of transparency remains essential because *"relevant monitoring should be implemented with the objective to provide information on the status of the performance of passive systems"* (WENRA, 2018, p. 12), it may appear insufficient in the context of T-H passive systems in the sense that the problem would not be one of "insufficient" information displayed, but rather of real information that is difficult to interpret due to specific operating characteristics directly related to the passivity of the passive system.

12.1.2. A potential increase in the importance of maintenance activities and rethink of maintenance strategy

The fact that T-H passive systems are highly sensitive to parameter variations and disturbances may lead to an increase in the importance of maintenance activities. This is the case, for example, regarding the pipes' inner surface condition, and particularly their roughness, which can influence heat transfer phenomena. Indeed, "*over time, a pipe becomes clogged and oxidized. And we wonder whether it will work in the way we imagine it will, but it won't work that way because it has aged*, etc. [...] *These are points of vigilance that we believe are more specific or more critical for this type of system. Because they will be much more sensitive in their operation to other details [...]. So, [during maintenance] we need to be vigilant about particular phenomena or with a different degree of tolerance*." (T-H researcher). In this context, it is therefore important to ensure that the pipes' inner surface condition does not show any deterioration or other damage that could affect the optimality of heat transfer phenomena. This is even more important as T-H passive systems are intrinsically characterized by thermo-hydraulic instabilities which can occur in single-phase or two-phase systems, and "may be at the origin of mechanical (e.g. vibrations are induced) and thermal (e.g. exceeding CHF and leading to high thermal stress) failures" (OECD-NEA, 2024, p. 261).

Furthermore, the fact that integration of T-H passive systems results in a simplified design and a reduction in the number of components (valves, pumps, etc.) on the sections of piping carrying primary fluid raises certain questions about the feasibility of maintenance work. Maintenance work requires sections of piping to be isolated. With fewer valves in particular, isolation techniques would most certainly need to be rethought[31].

In these above-mentioned examples, certain specific features of some T-H passive systems could question the reactor maintenance strategy. This point should be taken into account for new designs.

---

[31] An example will be illustrated in 12.3.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

12.1.3. A potential increase in the importance of operator training

The fact that T-H passive systems are difficult to test may be the reason why operators have less knowledge of these systems, which can have detrimental effects when these systems are in operation. Knowledge of the systems is indeed built up through opportunities to interact with them, and the high difficulty of testing them in representative conditions is problematic from this point of view.

Song & Kim (2014) illustrates this importance of operator training. During the Fukushima accident, it was shown that the isolation condenser of Unit 1, which is a T-H passive system and *"was the last resort for decay heat removal, was not properly operated, while the RCIC*[32] *functioned properly for a significant amount of time in the case of Units 2 and 3. It turned out that the operator was not fully trained for the operational characteristics of the isolation condenser, including the operational characteristics of the valves [of the system] […]"*[33] (Song & Kim, 2014, p. 214). The authors specify that this *"suggests that the operator should have enough training for the operation of the major safety system during a beyond-basis situation, like the one experienced in the Fukushima accident"* (Song & Kim, ibid).

The importance of operator training for the operation of major safety systems is even greater given that, as we mentioned regarding T-H passive systems, these systems could potentially create difficulties for operators in assessing their effectiveness (12.1.1).

12.1.4. A potential additional workload in the event of inadvertent actuation of T-H passive systems

The potential inadvertent actuations of T-H passive systems might result in additional workload that needs to be reconsidered in the operating schedule. These inadvertent actuations could also add additional control room activities, as they would require switching from normal operations to a recovery phase and a restart of the reactor. For example, in case of inadvertent safety injection actuation, these activities may involve restoring a borated tank to the proper boron concentration and recovering other systems prior to start-up.

12.2. Effects identified based on feedback from the operation of these systems within a real installation: the Passive Plant (PP)

Given the unique relationship these systems have with the environment in which they operate and considering that these initial findings presented in the previous section are based on a combination of interviews and existing literature, it became essential to compare these findings with actual facilities incorporating T-H passive systems. At the same time, this allowed us to try to move as closely as possible towards a "FROM" approach (9.2), meaning an approach that allows us to study the effects of T-H passive systems on human activities by examining them

---

[32] The Reactor Core Isolation Cooling system (RCIC) system *"is an auxiliary system of a boiling water reactor (BWR) that provides makeup water in the case of a severe accident"* (Lopez, Erkan & Okamoto, 2016, p. 1899). This is an active decay heat removal system present in Units 2 and 3 of Fukushima, while the isolation condenser in Unit 1 is a passive decay heat removal system.

[33] In this regard, the report of the Nuclear Accident Investigation Commission of Japan (NAIIC), published in 2012, states that *"The BWR Operator Training Center (BTC) only offers desktop exercises on severe accident operations defined by the manual to shift supervisors and deputy shift supervisors, with no operator training provided. Furthermore, its training simulators did not have the isolation condenser (IC) […]"* (p. 42) and that *"[…] it was the first time the [Isolation Condenser] automatically started and was ever used in Unit 1 since it started operation in 1971"* (p. 83).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

directly within the context of those activities. This approach establishes a link between these systems and human activities that is no longer hypothetical, as in the case of the "FOR" approach (9.2), since it is based on how the T-H passive systems are integrated into the activities themselves.

To this end, we conducted interviews with operators/trainers working at a nuclear power plant that incorporates such systems, while also deepening our technical understanding of this plant by reviewing technical documentation describing its specific passive systems. For confidentiality reasons, we will name this power plant the “Passive Plant” (PP). It is a Generation III+ pressurized water reactor (PWR) that features an innovative passive safety concept, requiring no operator actions to mitigate design basis accidents. This reactor design mainly consists of three T-H passive systems, which we have named systems A, B, and C[34]. We detail them in the table below.

System name	System components
System A - Passive Decay Heat Removal System	• Elevated gravity drain tank • Passive residual heat removal heat exchanger connected to RCS • *Associated valves*
System B – Passive Emergency Core Cooling System	• Elevated tank natural circulation loops • Pre-pressurized core flooding tanks (accumulators) • Elevated gravity drain tank • *Associated valves*
System C – Passive Containment Cooling and Pressure Suppression System	• Passive containment spray systems • *Associated valves*

Table 2 - Passive T-H passive systems integrated in the Passive Plant (PP)

For confidentiality reasons, we have renamed each of these systems and described their components using the generic terminology employed in IAEA (2009). Readers who wish to understand the role of each component in greater detail should refer to that document.

Finally, we would like to stress that all of the information shared in this section 12.2 (and then in the subsections 12.2.1, 12.2.2 & 12.2.3) relates solely to the operating experience of the Passive Plant.

12.2.1. Regarding the slowness of these systems

First, operating experience elements gathered confirm that the fact that these systems are characterized by a certain slowness of operation is to be stated with due care of the operating conditions. Indeed, feedback on the actuation of the System A shows that "the cooldown was extremely rapid and very effective [“It was well in excess of 100F/hour cooldown rate”]. So much so that it caused actuation of other safety systems [namely System B] based on automatic signals like plant low pressure and steam line low pressure. That's how fast they cooled it down and caused an actual safeguards actuation.". In connection with this, it is interesting to note that the Passive Plant (PP) design provides that, once the system A activation signals are activated, a forced flow is maintained for 5 seconds. One of the interviewees states that "*You get that initial push and differential temperature across the system instead of just having it do it all by itself and starting from zero and then working its way through. Yes, if you had to establish a differential*

---

[34] In this research, we focus on systems A and B. This focus was not intentional but rather emerged from the interviews with the participants from the Passive Plant (PP).

Co-funded by the European Union UK Research and Innovation The Research Council of Norway Project funded by Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra Swiss Confederation Federal Department of Economic Affairs, Education and Research EAER State Secretariat for Education, Research and Innovation SERI

temperature that they were not already established, it would take a long time to develop that thermal driving". In other words, if the operating experience elements of the Passive Plant (PP) allow us to relativize the slowness of the systems, the design choices specific to this reactor play obviously an important role in this relativization. This also confirms the importance of thinking about these systems in a real installation to be able to assume their efficiency and reliability.

We would point out that these elements seem to confirm that these T-H passive systems perform the safety functions for which they were designed (even if the conditions are not the same as those that would be encountered in an accident). Indeed, feedback about System A and System B shows that, *"[…] when the safety systems actuate, you're immediately going to cold shut down. They're going to cool you all the way down, way less than 200°".*

However, from a human activity perspective, this can lead to greater recovery efforts for operators to restart the plant. This point is well illustrated in the case of the direct entry into a cold shutdown: *"[…] the [Elevated tank natural circulation loops] themselves need to be cooled and reborated. In addition to that, the [Elevated gravity drain tank] now has to be cooled down from saturated conditions. Compare and contrast that to a legacy plant where a plant could remain in hot standby and a restart attempted in a shorter time"*. If these characteristics of the Passive Plant's T-H passive systems were to become widespread in the design of future passive reactors, it would necessitate a re-evaluation of resource allocation, particularly if the design includes a multi-unit control room.

12.2.2. Regarding the fact that operators are not expected to take action

Operating experience elements gathered show that, during the operation of these T-H passive systems, the operators could have done nothing: "There was nothing the operators could have done [to ameliorate the situation]. It was happening and they pretty much just had to watch […] it really is just a monitoring game". This seems to confirm that once the T-H-passive systems are activated, operators are not expected to do direct action on these systems to exert influence on their behaviour. When we go further into what the operators felt during this System A actuation and the impossibility of acting, it would seem that they were surprised by the speed of the system's action to cool down the plant, but "[The Passive Plant operators'] training program was successful in preparing the control room staff such that they were proficient in responding with […] emergency procedures. While initially surprised, it did not hinder entry and execution of emergency protocols".

12.2.3. An inability to disconnect T-H passive systems under certain conditions

Another interesting aspect of these Passive Plant T-H passive systems is that, under certain conditions, they cannot be disconnected. This may be not solely the result of the system's passivity, but may also be the result of complex interactions between this passivity and different factors:

- <u>Technical specifications</u>: on the Passive Plant, all passive safety systems must be available while there's fuel in the vessel. During outages, "they must be able to actuate to flood the core if that's required […]" - "[…] if there's fuel in the vessel, all those passive safety systems must be active, waiting";
- T<u>he integration of passive components into larger systems A & B</u>, within which they are highly interdependent in their influence on plant response. In other words, simply put, the different components of systems A and B are interdependent in their activation

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

signals, meaning that one component can activate another, depending for example on the level of borated water in the tanks or on pressure signals.

- One of the rationales behind their design is that they must activate in the event of signal loss, unlike active safety systems.

Complex interactions between these different factors result in the fact that "there is no way to really turn them off. The automatic signals are always there, ready to go". For example, "If any work requires draining the [Elevated tank natural circulation loops] or if there is maintenance on the level transmitters – signal coincidence for [another component of the system B] actuation can be satisfied. This requires […] defeating [this other component of the system B] actuation and thus can only be done once the core is offloaded. Even though [Elevated tank natural circulation loops] aren't required in this configuration – their inputs to [another component of the system B] are still active".

So, this inability to "disconnect" T-H passive systems under certain conditions presents a risk of inadvertent actuation that can complicate maintenance activities, in-situ testing, and refuelling activities during outages, and may even impose restrictions, particularly regarding their organization and sequencing.

12.3. Synthesis about HOF issues based on generic elements and operating experience of T-H passive systems

This exploratory research allows us to draw some conclusions regarding the HOF issues generated by T-H passive systems. The conclusions presented here incorporate and summarize elements highlighted in the generic results, identified from interviews unrelated to any existing plant design, as well as elements highlighted in the results specific to the Passive Plant.

First, since the natural phenomena on which these systems are based can cause unstable and oscillatory behaviour, control room operators may encounter difficulties in diagnosing the effectiveness of the system[35], even if all the necessary parameters are displayed, because it is precisely this information, which demonstrates the instability of the system's functioning, that could be disturbing. Regarding the transparency criterion, while the passive safety systems investigated in this research do not revolutionize the principle itself because operators will always need to have the necessary information to understand what is happening, **these systems do introduce a new dimension that stems directly from their phenomenal nature**. In other words, from a design perspective, beyond the criterion of transparency, it will be essential to help operators diagnose the effectiveness of the system, in addition to providing the parameters useful for this diagnosis. Furthermore, given that T-H passive systems can be difficult to test in conditions close to those in which they are expected to operate, and therefore operators may not have the opportunity to gain extensive knowledge about their operation, operator training becomes crucial. This training must particularly include familiarization with this type of unstable and oscillatory behaviour, which can differ significantly from that of conventional active systems.

---

[35] It is important to note that this result emerged from interviews conducted outside of any relationship with a real plant. Moreover, this difficulty does not appear to have been observed during safety system actuations on the Passive Plant. However, given the significant link between the operation of T-H passive systems and their integration into a specific environment and design, we are still reporting this result because the fact that this difficulty was not observed on the Passive Plant does not mean that it would not occur in another design or under other conditions.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by

Furthermore, on the question of the role of operators in the operation of passive safety systems, the findings highlighted in this report suggest that their **monitoring role could be exacerbated**, particularly during the operational phase, to ensure that passive systems are in the required condition for effective operation if called upon. In other words, while it seems clear that operators are not expected to do action for a long period once the systems are activated and in operation, the effectiveness of monitoring activities during operation is nevertheless of high importance with the objective of providing information on the status of the performance of passive systems. In this context, adequate procedural guidance should be established, and the feasibility of necessary human actions should be ensured in case of failure of passive safety systems function. Moreover, their sensitivity to actuate inadvertently is to be confirmed and considered in the future. As mentioned in 12.1.4 this sensitivity can lead to **additional recovery activities intended to restart the plant**. These additional activities should not be underestimated in the context of SMR development, where the aim is to reduce the number of operators in the control room while monitoring multiple reactors.

In addition, one of the findings that we consider important relates to maintenance activities, in-situ testing, and refuelling. Indeed, while T-H passive systems maintenance is potentially more critical due to their high sensitivity to parameter variations, the adequate definition of the condition of their testing should be then particularly accurate, which is a challenge for safety systems. Another characteristic could further complicate the situation: their greater propensity for inadvertent actuation. This can indeed lead to complications during maintenance, in-situ testing, and refuelling activities. In other words, while it is essential to consider the needs of control room operators regarding the operation of these passive systems, the potential impact of these systems on activities outside the control room should not be overlooked. This risk is even greater given that the reduction in the number of installed components resulting from the use of passive systems is often associated with the idea of limited maintenance activities, due to the reduced number of components. We believe it is important to emphasize that **a simplistic link should not be drawn too quickly between the reduction in the number of components requiring maintenance, made possible by the integration of passive systems, and the simplification of maintenance activities**. As an example, we can cite the need to isolate certain sections of piping to carry out various maintenance activities, which may be constrained by the reduction in the number of isolation valves. This translates into the need to find alternative ways of isolating these sections of piping, which will remain a maintenance requirement regardless of the design of the nuclear power plant, whether more or less active or passive, considered. Rather than leading to simplified maintenance, reducing components leads to the necessary implementation of alternatives such as freeze seals to ensure that maintenance activities can still be carried out. It seems that maintenance operations involving freeze seals cannot be considered “simplified” and require specific skills that must be developed among operators and/or sought from external partners.

13. Conclusion of these exploratory research

Through this exploratory research it was first necessary to precisely define what is meant by the concept of "passivity" in systems, to examine its potential impact on human activities. More specifically, from a HFE perspective, the objective was to determine to what extent the passivity of these systems would lead to similar or different requirements for performing tasks with automated or autonomous systems, and whether this would necessitate an evolution of the associated HFE design and evaluation principles, namely the concepts of transparency and explainability.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

For several reasons explained in this report, we chose to focus on T-H passive systems. After examining their technical characteristics and their potential effects on human activities through interviews with experts from various backgrounds and a literature review, we sought to understand these systems in a real plant. Indeed, the unique relationship these systems maintain—due to their inherent phenomenal or process-oriented nature—with reality meant that a generic approach to their operation was insufficient to yield conclusive results. Therefore, we conducted interviews with operators and trainers in a nuclear power plant that incorporates these systems, which, for confidentiality reasons, we have called the "Passive Plant" (PP).

However, even though this allowed us to access elements that emerge only from this encounter between T-H passive systems and reality, the more we sought to approach them, the more factors specific to this particular design came into play. In other words, even when approaching them in reality[36], their high dependence on their environment directs us towards factors that are very specific to the Passive Plant (PP) design, preventing us from generalizing about passive phenomena in absolute terms. So, where possible, we have taken care to identify the various factors at play in certain findings so as not to draw overly hasty and sweeping conclusions about the effects of “passivity” in general.

Finally, even though this exploratory research cannot provide entirely conclusive results, we identified interesting HOF issues raised by the T-H passive systems, explained in detail in the synthesis provided in 12.3. Beyond identifying these interesting HOF issues, this exploratory research also allowed us to experience the specific characteristics of a "FOR" ergonomics approach (9.2). Usually, we use a "FROM" approach, which is better suited to our conceptual framework. This “FROM” approach starts with human activities in concrete situations and contexts, allowing us to identify issues related to technical systems as they emerge from these activities. In other words, in the "FROM" approach, the specific issues raised by technical systems can be directly identified from the overarching activity that integrates them. In this report, we had to take an inverse approach, developing a "FOR" approach[37] that starts with identifying the technical characteristics of the systems, to establish a more or less hypothetical[38] link with their potential effects on activities.

In other words, our approach to the concrete situation and to the technical systems was reversed: here, we started from the generic characteristics of the systems to draw a link with the human activities that would develop in a concrete situation, whereas usually we start from this situation in which human activities take place and identify from there the technical aspects that raise questions. This reversal exposed us to many uncertainties and could sometimes cause confusion for us. For example, some experts told us that the defining characteristic of T-H passive systems was their reliance on natural phenomena such as natural circulation, and that, therefore, no human intervention would be possible. We listened to their expert opinion while questioning ourselves: was it possible to establish such a direct link between a physical phenomenon and the effects of T-H passive systems on human activities? The boundaries of these systems then raised questions for us: was the T-H passive system simply a closed thermal-hydraulic loop equipped with a heat exchanger? Were valves included, potentially allowing for human action?

---

[36] By "reality", here we mean a specific design that is fully developed and in operation.

[37] As indicated in 9.2, the impossibility of taking a “FROM” approach was due to several reasons, particularly the fact that T-H systems are underdeveloped and virtually inaccessible for observation from activities in real situations.

[38] This link is not, however, purely hypothetical, in that it is based on the researchers' knowledge of the activities in question (in this case, human activities in nuclear power plants, in the control room or in the field).

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

In retrospect, we can identify the different levels of understanding of T-H systems that we had to go through to reduce the uncertainties that were causing us concern. These different levels of understanding are illustrated in Figure 2. Ascending through the different levels allowed us to better understand how they will be implemented in a real plant and, at the same time, to define their “boundaries” (does the thermal-hydraulic loop constitute the passive system itself or is it a passive component integrated into a larger system?). This notion of “boundaries” was particularly confusing at the outset of our research. It seems important to us to emphasize that, at the end of this research, we understand that these boundaries must be considered in relation to the safety function to be ensured. When we began the interviews to understand what a passive system was, we were personally confused when certain people talked to us about passive systems for a “siphon breaker” or an “accumulator,” without us being able to understand in what way they constituted systems as such. We lacked a framework for understanding these systems within a broader context. This framework corresponds to the boundaries of the systems involved in ensuring a safety function. In this framework, on legacy plants, the accumulator is more of a passive component integrated into a larger system – the Emergency Core Cooling System (ECCS) - composed of active and passive components in order to perform the safety injection. In other words, at the end of this research we understand that on legacy plants this accumulator is more of a component than a passive system, even though a majority of people interviewed spontaneously speak of this accumulator when we ask them to define and give examples of passive systems.

In other words, moving through these different levels is essential for establishing the link between the characteristics related to the passivity of the systems and human activities because, the higher we go up the levels of understanding, the closer we get to a "real-world" situation, and the better we are able to identify the effects of T-H passive systems that will be observed once they are integrated into actual installations.

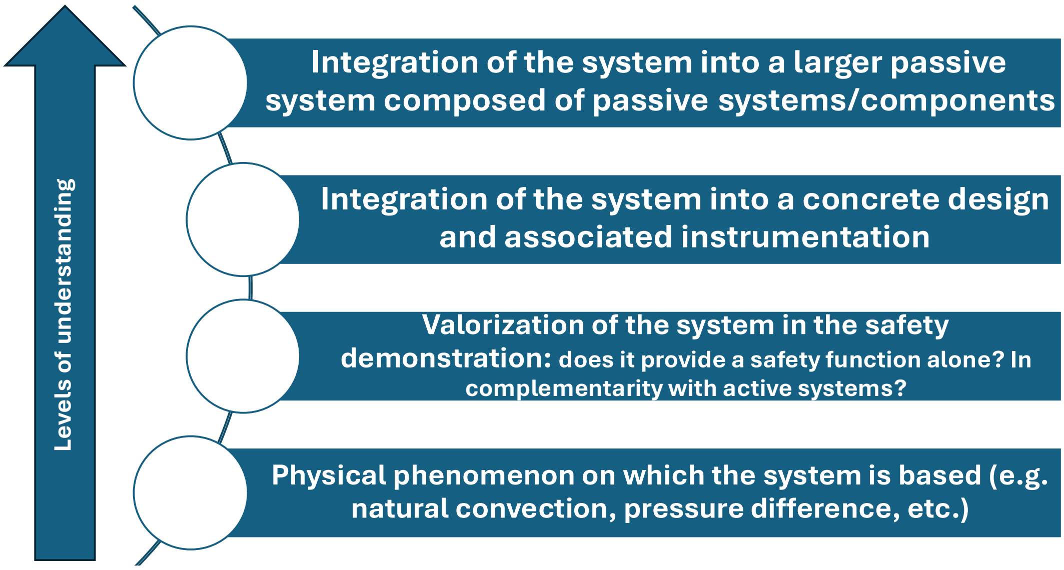

Figure 2 - Different levels of understanding of T-H passive systems

Initially, we believed that these uncertainties and the need for these different levels of understanding of T-H passive systems were specific to our ergonomics perspective and to the fact that we could not approach these systems in an ideal way, i.e., based on the actual activities of the people who interact with them, with a “FROM” approach. But rather than being a consideration specific to a particular discipline, it seems that this need is not specific to any one discipline but rather applies to any discipline that seeks to acquire knowledge about T-H passive systems operation if it cannot be based on a real-world implementation. These uncertainties are indeed reflected in practice in the work of T-H researchers or experts seeking to qualify codes to simulate the functioning of these systems: "*It's not easy to run simulations because we don't have the geometric data; no manufacturer is going to give us anything at the moment.*" (Simulation & code qualification expert). One of the T-H passive systems experts points out that one of the big questions concerns the transferability of tests to actual design and actual construction "*because the slightest change, even in terms of geometry, will have an influence on the flow and therefore on potential oscillations. The oscillations we saw in the experiment may not exist in our reactor case, and the reverse is also possible*". In other words, the various disciplines involved in acquiring knowledge about these T-H passive systems face uncertainties that stem from inherent characteristics of these systems and their particular link to reality. We believe that, in this context, the different levels of understanding of T-H passive systems presented in Figure 2 can serve as the basis for alternative categorizations of passive systems, different from the one proposed by the IAEA. In our case, these categories are more useful to us because they help us better understand these systems by focusing on concrete elements, rather than a categorization based solely on identifying whether these systems are more or less passive.

Finally, as indicated in the introduction, this deliverable is the first step in the ongoing acquisition of knowledge on this subject over the four years of the EASI-SMR project. The next step will be to incorporate some of the elements highlighted here into the design of scenarios that will be played out in the multi-unit control room simulator owned by IFE (Halden)[39]. The aim will then be to analyse the activity of the control room operators who will have been recruited for the occasion and who will be responsible for operating the facility incorporating these systems. This will provide a different opportunity to acquire knowledge about these systems by simulating them as closely as possible to a real-life situation.

14. Bibliography

Abram, T., & Elshahat, A. E. (2012). Advanced nuclear reactors and passive safety. In G. Petridis, & D. Nicolau, *Nuclear power plants* (pp. 41-67). Nova Science Publishers, Inc.

Beer, J. M., Fisk, A. D., & Rogers, W. A. (2014). Toward a Framework for Levels of Robot Autonomy in Human-Robot Interaction. *Journal of Human-Robot Interaction, 3*(2), 74-99.

Burgazzi, L. (2002). Passive systems analysis for decay heat removal. In OECD-NEA, *Passive system reliability - A challenge to reliability engineering and licensing of advanced nuclear power plants* (pp. 106-117). NEA/CSNI/R(2002)10.

Burgazzi, L. (2007). State of the art in reliability of thermal-hydraulic passive systems. *Reliability Engineering and System Safety*(92), 671-675.

Burgazzi, L. (2012). Reliability of passive systems in nuclear power plants (Chapter 2). In *Nuclear Power - Practical aspects* (pp. 23-58). Ahmed, Wael H.

Compan, N., Brunet, B., Mestanza, M., Renonciat, A., Monéger, F., Récopé, M., . . . Coutarel, F. (2023). Concevoir des dispositifs intégrant une technologie autonome: du technique au politique. *Activités, 20*(1).

Daniellou, F. (2005). The French-speaking ergonomists' approach to work activity: cross-influences of field intervention and conceptual models. *Theoretical Issues in Ergonomics Science, 6*(5), 409-427.

---

[39] Significant work remains to be done in designing these scenarios, which must incorporate 1) the specific features of passive safety systems that may have an impact on operation, which we wish to simulate; 2) Typical accidents considered in the nuclear industry (LOCA, SGTR, etc.); 3) Operating conditions: do we want to simulate only the incidental-accidental conditions in which these systems are required, or also normal conditions in which these systems may actuate inadvertently?

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Daniellou, F., & Rabardel, P. (2005). Activity-oriented approaches to ergonomics: some traditions and communities. *Theoretical Issues in Ergonomics Science, 6*(5), 353-357.

D'Auria, F. (2018). Status report on Thermal-Hydraulic passive systems design and safety assessment. *Invited at focus session Safety of advanced Nuclear Power Plants on the Annual Meeting on Nuclear Technology (ANMT).* Berlin.

Dul, J., Bruder, R., Buckle, P., Carayon, P., Falzon, P., Marras, W. S., . . . van der Doelen, B. (2012). A strategy for human factors/ergonomics: developing the discipline and profession. *Ergonomics, 55*(4), 377-395.

(https://snetp.eu/wp-content/uploads/2023/07/European-SMR-pre-Partnership-WS5-report-and-roadmap-30-June-2023.pdf). *European SMR pre-Partnership Workstream 5 – Research, Development, and Innovation Roadmap.*

Freis, D., Haspel, N., & Tietsch, W. (2009). AP1000TM Nuclear Power Plant Passive Safety System Actuation using Explosively Opening "Squib Valves". *International conference on opportunities and challenges for water cooled reactors in the 21st Century, IAEA.*

Gouraud, J., Delorme, A., & Berberian, B. (2017). Autopilot, Mind Wandering, and the Out of the Loop Performance Problem. *Frontiers in Neuroscience, 11*.

Hendrick, H. W. (2002). An Overview of Macroergonomics. In H. W. Hendrick, & B. M. Kleiner, *Macroergonomics. Theory, Methods, and Applications* (pp. 1-23). Mahwah, NJ: Lawrence Erlbaum Associates.

IAEA. (1991). *Safety related terms for advanced nuclear plants.* IAEA-TECDOC-626.

IAEA. (2009). *Passive Safety Systems and Natural Circulation in Water Cooled Nuclear Power Plants.* IAEA-TECDOC-1624.

IAEA. (2012). *Natural Circulation Phenomena and Modelling for Advanced Water Cooled Reactors.* IAEA-TECDOC-1677.

IRSN. (2016). *Considerations on the performance and reliability of passive safety systems for nuclear reactors.* https://research-assessment.asnr.fr/sites/en/files/2023-09/IRSN_Passive-safety-systems-for-nuclear-reactors_01-2016.pdf.

Karran, A. J., Demazure, T., Hudon, A., Senecal, S., & Léger, P.-M. (2022). Designing for Confidence: The Impact of Visualizing Artificial Intelligence Decisions. *Frontiers in Neuroscience, 16*.

Lopez, H., Erkan, N., & Okamoto, K. (2016). Reactor core isolation cooling system analysis of the Fukushima Daiichi Unit 2 accident with RELAP/ScdapSIM. *Journal of nuclear science and technology, 53*(11), 1899-1905.

Matzie, R. A. (2008). AP1000 will meet the challenges of near-term deployment. *Nuclear Engineering and Design*(238), 1856-1862.

Montout, M. (2024). *PASTELS D5.6: Roadmap for European versions of SACO and CWC.*

Myklebust, T., Stalhane, T., & Vatn, D. M. (2025). *The AI Act and The Agile Safety Plan.* SpringerBriefs in Computer Science.

OECD-NEA. (2002). *Passive system reliability - A challenge to reliability engineering and licensing of advanced nuclear power plants.* NEA/CSNI/R(2002)10.

OECD-NEA. (2024). *Status Report on reliability of Thermal-Hydraulic Passive Systems.* NEA/CSNI/R(2021)2.

O'Hara, J., Higgins, J., & Deem, R. (2010). Human Factors Aspects of Operating Small Reactors. *Presented at the Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC &HMIT 2010).*

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on systems, man, and cybernetics - Part A: Systems and Humans, 30*(3).

Poizat, G., & San Martin, J. (2020). The course-of-action research program: historical and conceptual landmarks. *Activités, 17*(2). Retrieved from https://journals.openedition.org/activites/6434

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Poret, C., Folcher, V., Motté, F., & Haradji, Y. (2016). Designing for the Power to Act Together in organisations: the case of a business process. *Activités, 13*(2).

Rabardel, P., & Béguin, P. (2005). Instrumented mediated activity: from subject development to anthropocentric design. *Theoretical Issues in Ergonomics Science, 6*(5), 429-461.

Saghafian, M., Vatn, D. M., Thordarson Moltubakk, S., Bertheussen, L. E., Petermann, F. M., Johnsen, S. O., & Alsos, O. A. (2025). Understanding automation transparency and its adpative design implications in safety-critical systems. *Safety Science, 184*.

Schulz, T. (2006). Westinghouse AP1000 advanced passive plant. *Nuclear Engineering and Design*(236), 1547-1557.

Skraaning, G., & Jamieson, G. A. (2021). Human performance benefits of The Automation Transparency Design Principle: Validation and Variation. *Human Factors, 63*(3), 379-401.

Song, J. H., & Kim, T. W. (2014). Severe accident issues raised by the Fukushima accident and improvements suggested. *Nuclear Engineering and Technology, 46*(2), 207-216.

The National Diet of Japan. (2012). *The official report of The Fukushima Nuclear Accident Independent Investigation Commission.*

Theureau, J. (2006). *Le cours d’action : méthode développée.* Toulouse: Octarès Editions.

WENRA/RHWG. (2018). *Report "Regulatory Aspects of Passive Systems".*

WENRA/RHWG. (2021). *Report "Safety Reference Levels for Existing Reactors 2020".*

Wilson, J. R. (2014). Fundamentals of systems ergonomics/human factors. *Applied Ergonomics, 45*, 5-13.

Co-funded by the European Union
UK Research and Innovation
The Research Council of Norway
Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

EASI SMR