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ELSMOR

Towards European Licensing of Small Modular Reactors

PIRT for heat removal from the containment with passive safety features

WP 4: Improved Safety Analysis Methods and Tools for Containment Safety

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Report's title

PIRT for heat removal from the containment with passive safety features

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Summary

The report describes the elaboration of a PIRT (Phenomena Identification Ranking Table), with focus on phenomena identified as being of importance regarding the containment safety functions of LW-SMR. The identification of significant T/H phenomena involved in the behaviour of the SMR should cover normal and accidental conditions considering DBC and DEC conditions. The main result is a matrix containing relevant phenomena necessarily to be considered to support a better understanding and assessment of the safety functions in the containment, water pools within and outside of the containment, and the heat transfer from and to the containment shell. Two designsn were selected as of major interest. In compliance with the ELSMOR project the French NUWARD concept was the obvious choice. In addition, the NuScale concept was chosen since it is in an advanced state and recently received design certification approval from the U.S. NRC.

The main result is a matrix containing relevant phenomena necessarily to be considered to provide a better understanding of the safety functions in the containment, water pools within and outside of the containment and the heat transfer from and to the containment shell.

The authors recommend reviewing the PIRT as soon as precise information is available.

Confidentiality	Public

Petten, 14.3.2021

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Abbreviations

ARIS	Advanced Reactors Information System (OECD)
ATWS	Anticipated Transient Without SCRAM
CFR	Code of Federal Regulations (U.S.)
CSG	Compact Steam Generator
CSNI	Committee on the Safety of Nuclear Installations
DBC	Design Basis Condition
DEC	Design Extension Condition
ECCS	Emergency Core Cooling System
EDSS	highly reliable DC power system to supply essential loads
ELSMOR	Towards European Licencing of Small Modular Reactors
F-SMR	French Small Modular Reactor (recently announced as NUWARD)
FOM	Figure Of Merit
IAEA	International Atomic Energy Agency
IVR	In-Vessel Retention
LBLOCA	Large Break Loss Of Coolant Accident
LOCA	Loss Of Coolant Accident
LP	LOCA Phenomenon in PIRT tables
MCP	Main Coolant Pumps
MPS	Module Protection System
NEA	Nuclear Energy Agency
NPM	NuScale Power Module
NuScale	U.S. SMR design
NUWARD	French SMR design
OECD	Organisation for Economic Co-operation and Development
P	Phenomenon in PIRT (applicable to LOCA and SBO scenario)
PAR	Passive Autocatalytic Recombiner
PHRS	Passive Heat Removal System
PIRT	Phenomena Identification Ranking Table

RPS	Reactor Protection System
RPV	Reactor Pressure Vessel
RRV	Reactor Recirculation Valves
RVV	Reactor Vent Valves
SACO	SAfety COndenser
SBO	Station Black Out
S-CSG	Safety-Compact Steam Generator
SMART	System-integrated Modular Advanced ReacTor (Korea)
SMR	Small Modular Reactor
SP	SBO Phenomenon in PIRT
U.S. NRC	United States Nuclear Regulatory Commission
UHS	Ultimate Heat Sink

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1. Introduction

The ELSMOR (towards European Licencing of Small Modular Reactors) project seeks to enhance the capability of the European research community and industry to assess and develop innovative Small Modular Reactor (SMR) concepts and their novel safety features. The work aims both at investigating the safety of the Light Water Small Modular Reactors (LWSMR) holistically and at drilling down into the set of topics identified by the consortium to be the most vital in ensuring the compliance of the future SMRs to the safety objectives as established by the amended Directive 2009/71/Euratom /EUR 14/.

Work Package 4 (WP4) objective of the ELSMOR project /ELS 18/ is the development, assessment, and validation of analyses methods and tools for the safety demonstration of improved or innovative containment safety function features of integral LW-SMRs. As one task and the starting point of this WP, the elaboration of a PIRT (Phenomena Identification Ranking Table) with focus on relevant phenomena identified as being of importance regarding containment safety functions has been planned. This report describes the elaboration of this PIRT by characterizing and assessing the relevant phenomena for heat removal from the containment with passive safety features as identified in WP 1 and discussed in WP 2. There is also a connection to WP 3, where relevant phenomena in passive safety systems for heat removal from the core with passive safety systems are discussed. To fulfil these requirements, two-phase-flow natural circulation loops (connecting internal steam generator modules or specific internal heat exchangers to external, in-pool condensers or directly to the waterpool) are considered as the most important decay heat removal system towards the Ultimate Heat Sink (UHS) in almost all the integral pressurized water small modular reactor concepts. The identification of significant T/H phenomena involved in the behaviour of the SMR should cover normal and accidental conditions considering DBC (Design Basis Conditions) and DEC (Design Extension Conditions). Severe accidents including core degradation are only touched with view to T/H phenomena that are closely connected to the passive safety features. Fission product release and behaviour that is obviously also influenced by the performance of passive systems are out of the scope of this work.

An important outcome should be the identification and assessment based on expert judgement of both, phenomena or physical processes, their mathematical modelling, and experimental data needed to evaluate the safety function behaviour and gaps still existing and necessarily to be closed in whatever field. This is usually done relative to a specific objective, so called Figure Of Merit (FOM), that is in this case the assurance of containment integrity by keeping its pressure well below design limits. The PIRT not necessarily presents a closed process, rather it is a tool to provide guidance for the subsequent steps /USN 05/.

As part of this WP, the PIRT also serves as an input for the next task, the identification of significant experiments available in the open literature covering phenomena as identified in the PIRT (focused on the reference SMR concept safety features). The outcome will be an experimental matrix, which can be used to assess the applicability of codes. In addition, in case knowledge gaps are identified, the proposals for new experiments will be made if necessary or theoretical test case could be envisaged to apply codes in terms of a benchmark to such case. Through the PIRT elaboration and code application valuable conclusions can be drawn with view to the ability of the codes to cope with requirements.

2. Previous PIRT activities

The Phenomena Identification and Ranking Table (PIRT) process was developed in the late 1980s by the US Nuclear Regulatory Commission (NRC) and its contractors to support the introduction of the best estimate plus uncertainty analysis method as a new licensing option for emergency core cooling systems in the United States /SHA 88/. More precisely, the PIRT process aimed at helping establish relevant regulatory requirements to be imposed on phenomenological models used in the best-estimate computational tools. In its original form, the process involved systematic identification and ranking of physical phenomena that dominate the response of a reactor system under a postulated accident scenario, based on their influence on safety criteria.

Today, PIRT is a commonly used tool in the field of nuclear safety analysis. Though there is a common understanding about the scope of such tables, their implementation and thus the outcome often differ, depending on the framework under which the corresponding activities took place. The following overview is meant as an overview, it does not claim to be exhaustive. Nevertheless, it served as an additional input in setting up the present PIRT. Specifying boundary conditions for which the PIRT is prepared is necessary for clearly establishing its frame of applicability.

As regards SMR topics, more precisely passive safety features, comprehensive surveys have been performed. For NuScale, the most cited PIRT /NUS 13/ describes the development of the small-break loss-of-coolant accident (SBLOCA) phenomena identification and ranking table (PIRT) for the NuScale Power LLC (NuScale) passive modular integral power reactor. The purpose of that PIRT was to provide an assessment of the relative importance of phenomena that may occur in the NuScale module during accident conditions in relation to specified figures of merit. This assessment is part of the process prescribed by Regulatory Guide 1.203 (Reference 7.1.1) /USN 05/and will support development of a detailed evaluation model to serve as the calculation framework for analysis of SBLOCA scenarios in accordance with the acceptance criteria of 10 CFR 50.46 (Reference 7.1.2)."

A PIRT established as part of the EURSAFE thematic network was part of a concerted action in the sixth framework programme of the European Commission /MAG 04/. It strived for consensus among the main actors in nuclear safety on the severe accident issues where large uncertainties existed and still subsist. The conclusions were derived from a first-of-kind phenomena identification and ranking tables (PIRT) on all aspects of severe accident also realised in the frame of the project. Starting from a list of all severe accident phenomena containing approximately 1000 entries and established by the twenty partner organisations, 106 phenomena were retained eventually as both important for safety and still lacking sufficient knowledge. A severe accident database structure was proposed to ensure preservation of experimental data and enhanced communication for data exchange and use for severe accident codes assessment. As the result of an action involving R&D governmental institutions, regulatory bodies, nuclear industry, utilities and universities from six EU Member States plus JRC, European third countries, and USA, EURSAFE represents a significant step towards harmonisation and credibility of the approaches, and resolution of the remaining severe accident issues.

Another PIRT of interest was elaborated in the framework of the SMART (System-integrated Modular Advanced ReacTor) development /CHU 09/. Like the work in this WP, at that time the SMART design was under development, hence the result of PIRT was based on the currently available information of design and thus the PIRT results considered as preliminary.

As a last example, a PIRT has also been produced in the aftermath of the 2011 Fukushima Daiichi nuclear power plant accident /SUE 15/.

Worth mentioning also is the fact that usually the PIRT runs through several phases in particular in the early design phase where reviews and updates are common, as was mentioned for the NuScale design. This fact has also to be taken into account in doing the current PIRT when considering the current NUWARD design. Since comprehensive data is not available at the time of these WP activities, the outcome might have to be reviewed with the availability of more detailed information.

3. Innovative containment safety features

The integration of the primary circuit in the Reactor Pressure Vessel (RPV), and the limitation in number, length, and size of piping in the containment are characteristic of SMRs. Their components and systems can be shop fabricated and then transported as compact modules to the sites for installation. In the different SMR concepts currently either in the construction, design or concept phase – some of them are analysed in ELSMOR – these features are pushed to different degrees and have been employed to design containments with novel common features /EUR 14/:

- The smaller reactor size in terms of fission power reduces the size of the piping, eliminating large-break loss of coolant scenarios (LBLOCA)
- the elimination of the LBLOCA allows the containment size to be reduced significantly, sometimes even drastically, without risking pressure peaks that exceed the containment design pressure
- the small power, and thus small residual heat, of SMR modules makes concepts for natural-convection heat removal feasible
- the location of reactor modules in a large water-pool that acts as an ultimate heat sink (UHS) allows the realisation of long-term passive heat removal systems from the core to the UHS.

A comprehensible source, though general, is provided in the IAEA booklet on the status of SMR technology developments. It was first published in 2011 and is updated on a regular basis. The most recent version published in 2020 /IAE 20/.

The following subsections describe features of concepts analysed. The focus is on those concepts that facilitate a large water-pool as the UHS, i.e. the recently presented NUWARD and NuScale design. The latter has received U.S: Nuclear Regulatory Commission design approval in 2020.

According to /INT 14/ the wording ‘passive safety design options’ denotes various possible combinations of inherent and passive safety features and reasonable combinations of active and passive systems incorporated in reactor design, such as those incorporating moving fluids or expanding solid structures, direct action devices, or stored energy sources that generally require validation and testing to demonstrate and prove their reliable operation and, if necessary, adjust their design. While the individual processes are well understood, the combinations of these processes, which define actually the performance of such systems, may vary depending on changes in the conditions of state, boundary conditions and failure or malfunctioning of components within the system.

In the following sections, some concepts establishing a water pool as the UHS will be briefly presented, whereas the focus is on those concepts considered in the PIRT.

3.1 NUWARD™

Since almost all the documentation on NUWARD™ is proprietary and only available to the ELSMOR consortium, little can be written in this public document. What can be found in the open literature /CHE 20/ concerns general information e. g. on the size of the containment (height ~16 m, diameter ~15 m). The reactor core, control rod drive mechanisms, 6 compact steam generators and the pressurizer are all integrated in the RPV. Two separate safety compact heat exchanger also integrated in the RPV, are available under transient and accident scenarios. They are directly connected to an intermediate cooling circuit, where heat is transferred via two condensers to a coolant circuit directly connected to the water pool, where the containment is located (Figure 3.1, Figure 3.2) /IAE 20/.

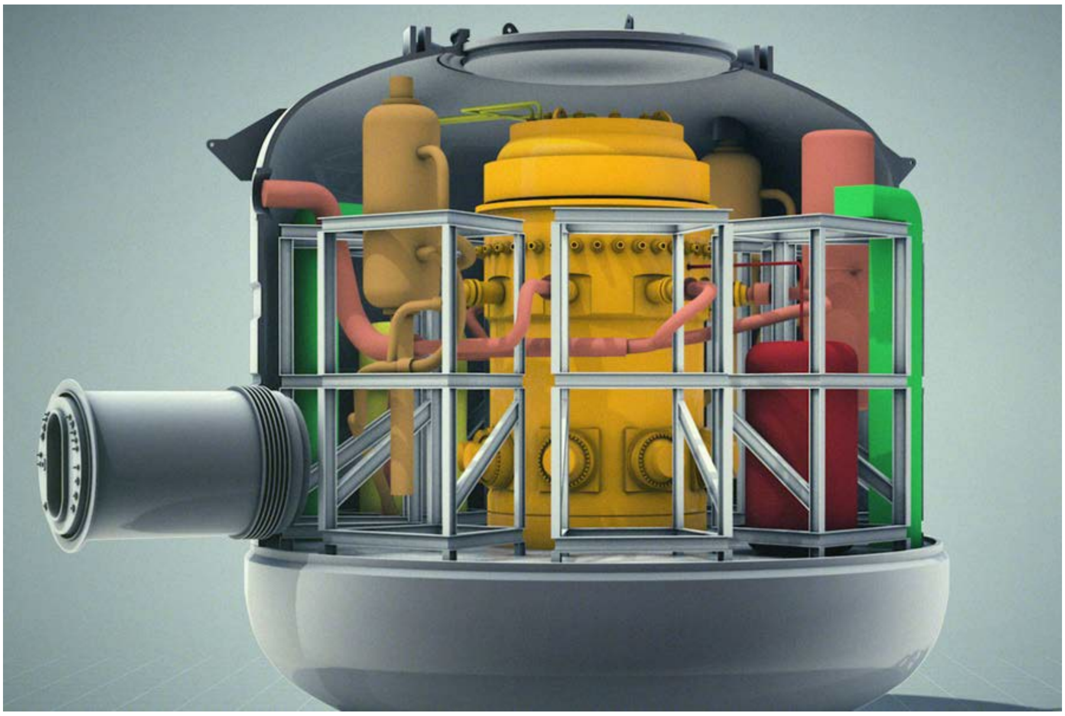

Figure 3.1 Design concept for one unit of the NUWARD SMR

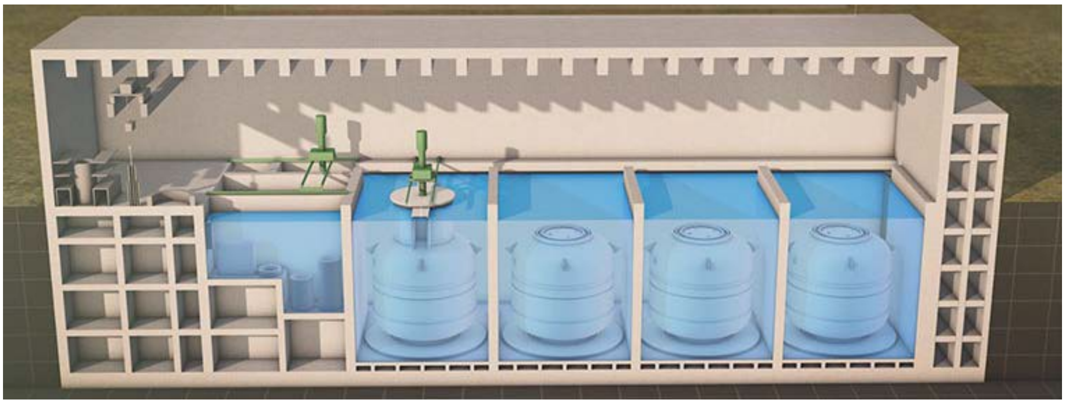

Figure 3.2 Design concept for plant layout of NUWARD SMR

On residual heat removal, available information points out:

"The design includes a 2x100% train of passive heat removal system transferring by natural convection the decay heat from the core to the UHS (termed waterwall in NUWARD concept) surrounding the containment. Each train is actuated by 2 diversified channels (diversified cause, diversified I&C and diversified actuator). The small diameter of the LOCA and the efficient passive heat removal system lead to a slowed down water loss during the first phase of the accident; a set of 2 redundant low-pressure safety injection accumulators provides the make-up of water inventory inside the vessel. In the longer term (after 3 days), an active system provides the make-up inside the vessel (~10^{m3}/day) from recirculation of water located on the bottom of the containment. The water-wall surrounding the containment ensures the heat removal function for more than 3 days without the need for an external ultimate heat sink."

On confinement and containment protection, the same documents describe:

"The steel containment submerged in the pool contributes to safeguarding the confinement function. The small diameter of the LOCA and the efficient passive heat removal system lead to a limited pressure inside the containment despite its small size. The steel containment is cooled passively by the surrounding pool. The containment is protected against small DBC hydrogen leaks by passive autocatalytic recombiners (PAR)."

Key information taken from this description, see also Figure 3.1, as illustration for the containment analysis is:

- As part of the Passive Heat Removal System (PHRS) the SAfety COndenser (SACO) in the containment communicates directly with the waterwall. Basically, a sufficient water level in the waterwall is required during up to 7 days to provide thermal inertia and allow the natural-convection heat removal loop with the SACO to function. When necessary (after 7 days or less), the ultimate cooling system or water make-up system of the waterwall can be activated.

- The steel containment placed in the pool will allow significant condensation of steam on, and by this heat removal from the containment inside wall. This is also a key element of the passive In-Vessel Retention (IVR) feature. However, no engineered safety system is described for a further heat removal through the containment wall.

- It has still to be analysed whether gradual evaporation of the UHS will reduce the capacity to remove decay heat from the core.

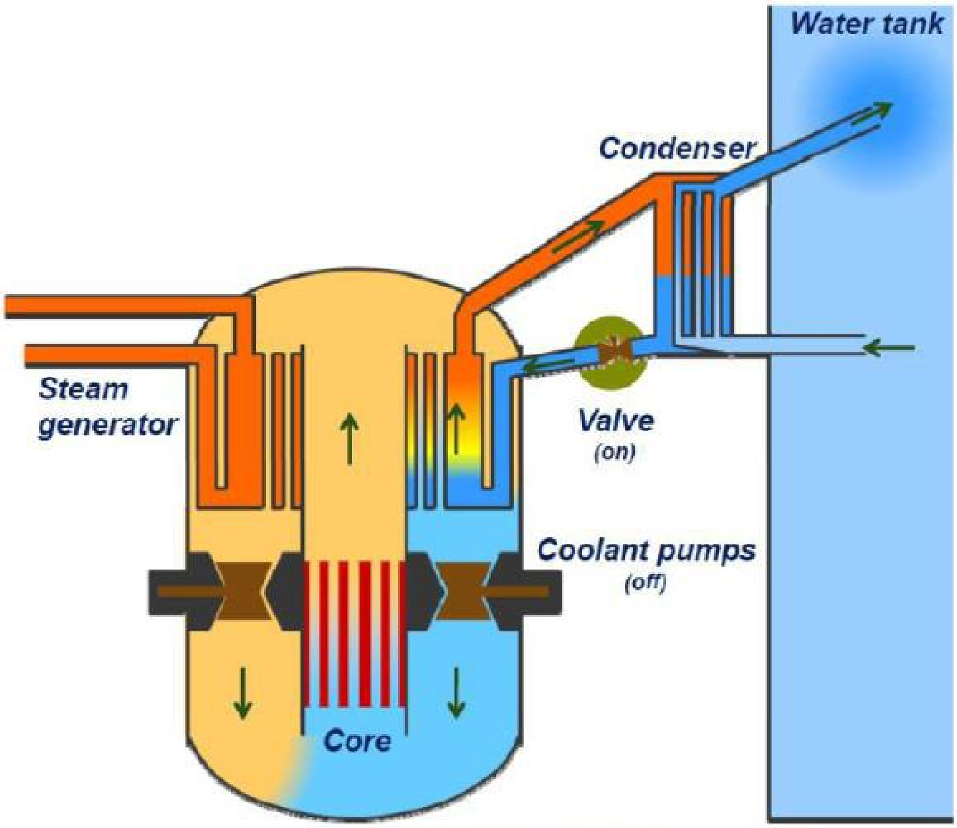

Figure 3.3 NUWARD passive heat removal system

According to the Defence-in-Depth criteria, additional systems are provided to cope with postulated multiple failure accidents and core melt accidents. In general, these systems are shared between the different reactors in the same plant, except for accidents related to common mode hazard (e.g. ATWS and earthquake).

“DEC-A systems are:

- Low-flowrate Depressurization system associated to active injection of clear water. These systems provide the removal of the decay heat in case of postulated common mode failure of redundant trains of passive DBC safety systems.
- High-pressure borated water accumulator to cope with ATWS accidents.

DEC-B systems are:

- Low flowrate Depressurization system to reach a primary pressure less than 2 MPa before core melting,
- Passive flooding of vessel pit in order to provide in-vessel retention of corium,
- Nitrogen injection to manage the hydrogen risk.”

3.2 NuScale Power Module™

The power plant will consist of up to twelve NuScale Power Modules (NPM), each rated at producing 60 MW of electricity (MWe)[1].

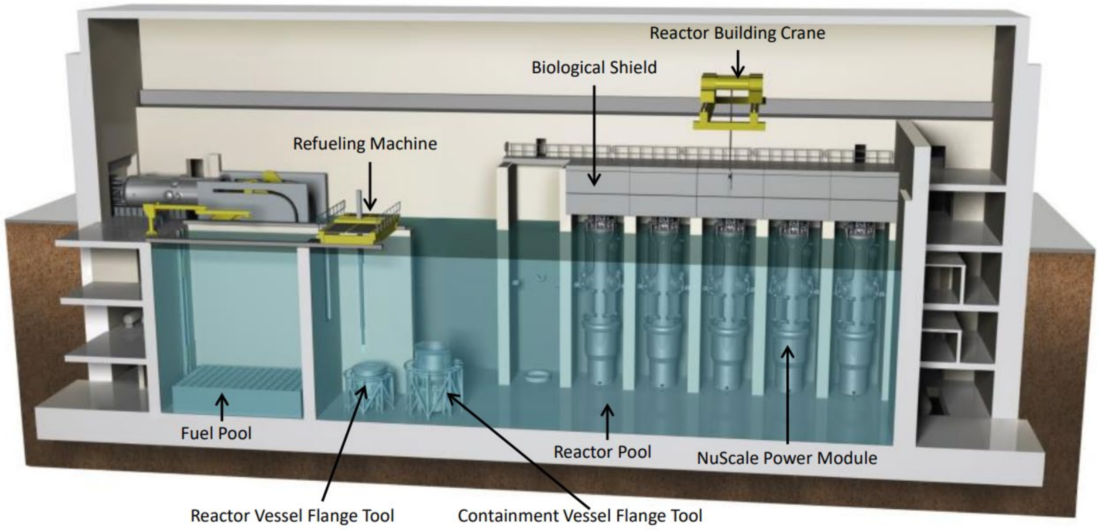

Figure 3.4 NuScale plant layout

Information on NuScale is based on the safety design report published on the US-NRC home page /NUS 19/ and on the Advanced Reactors Information System (ARIS) database at IAEA [2]. Key points for the containment safety function are:

[1] Recently, the design was updated to an output of 77 MWe (source: https://www.nuscalepower.com/)
[2] https://aris.iaea.org/PDF/NuScale-NPM200_2020.pdf

The plant reactor building cooling pool that is housing the SMR modules is used as UHS for the SACO of the safety-SG loop during the action of the PHRS. The SACO is located in the water pool, i.e. outside the SMR containment (CNV), cf. Figure 3.5 /ING 14/.

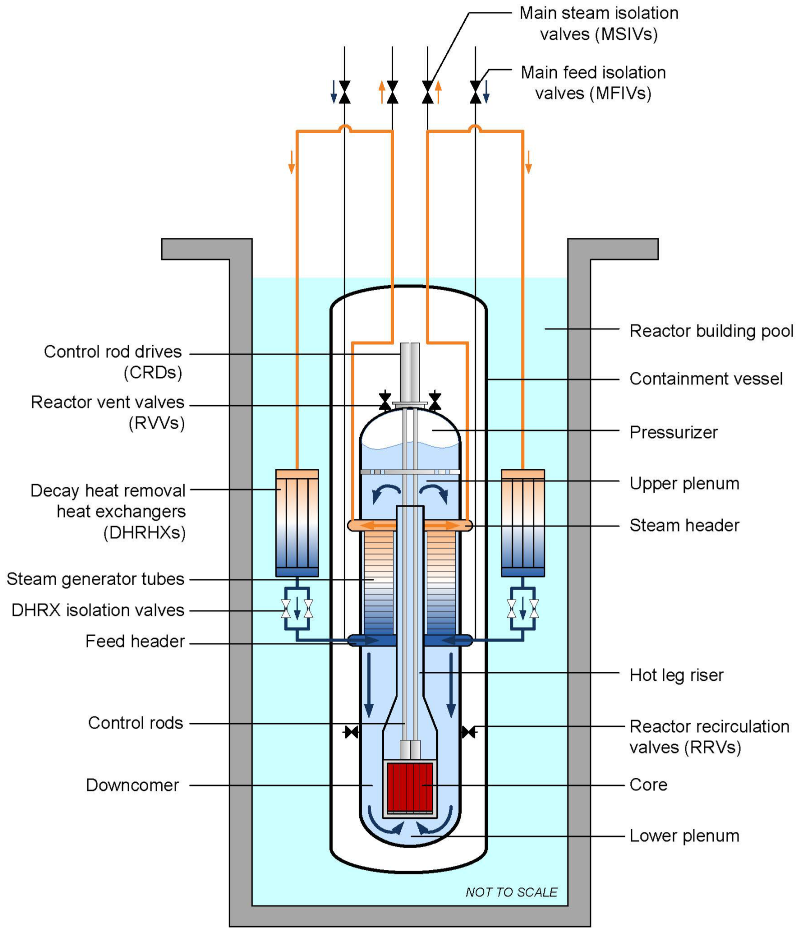

Figure 3.5 NuScale containment and passive heat removal system

During normal operation the containment is evacuated to keep heat losses from the core low. A non-safety-related containment flood and drain system exists to fill the containment with water, e.g. when heat removal through the containment shell is used to go from stable shutdown conditions to cold conditions.

An Emergency Core Cooling System (ECCS) to be used during a LOCA is described where the normally empty containment is flooded and valves inside the RPV, and between RPV and containment (Reactor Vent Valves), are opened to create a natural convection loop between the core and the containment wall as the heat sink (and passing this heat to the cooling pool as UHS).

The Decay Heat Removal System (DHRS) provides secondary side reactor cooling for non-LOCA events when normal feedwater is not available. The system is a closed-loop, two-phase natural circulation cooling system. Two trains of decay heat removal equipment are provided, one attached to each SG loop. Each train is capable of removing 100 percent of the decay heat load and cooling the RCS. Each train has a passive condenser immersed in the reactor pool. In the event of a SG-tube failure, the affected SG is isolated and the DHRS provides cooling through the intact SG. On receipt of an actuation signal, feedwater and main steam isolation valves are closed and the DHRS valves open. Reactor coolant continues to circulate through the RPV, collecting decay heat from the core. As water from the DHRS condenser travels through the SG tubes it is converted to steam absorbing decay heat from the reactor coolant. The steam then flows back to the DHRS condenser where it gives up excess heat to the reactor pool water and is condensed, and the cycle is repeated. This transfer of heat promotes natural circulation in both the RCS and the DHRS. (NUSCALE, NuScale Standard Plant Design Certification Application Chapter One Introduction and General Description of the Plant PART 2 – TIER 2).

Advantageous for the passive heat transfer to the UHS is the lack of insulating material on both the reactor vessel and the CNV. Following a LOCA, or RSVs cycling, primary coolant accumulates in the containment to the point that the lower reactor vessel becomes submerged. For transients in which RSVs have cycled, the temperature inside the RPV is sufficiently high that heat transfer to the water collected in the containment becomes greater than decay heat levels. This condition occurs after several RSV cycles after which the RPV pressure approaches the containment pressure and RSV cycling stops. ECCS is demanded and natural circulation cooling is established through the RVVs and RRVs. For the remainder of the event, decay heat is accommodated by transferring it passively (by conduction and convection) through the uninsulated vessel wall to the coolant that has collected in the containment. Similarly, heat is transferred passively (by condensation, conduction and convection) to the UHS through the containment wall.

An assumed generic failure occurring inside the containment results in the release of all 46,700 kg of primary coolant from the RCS to the containment. In a design basis accident involving a sustained loss of all AC power, decay heat is removed from the NuScale Power Module (NPM) through passive heat transfer to the pool resulting in pool heat up and eventual boiling. Water inventory in the reactor pool is adequate to cool the NPMs for at least 72 hours without adding water (cf. Figure 3.6[3]).

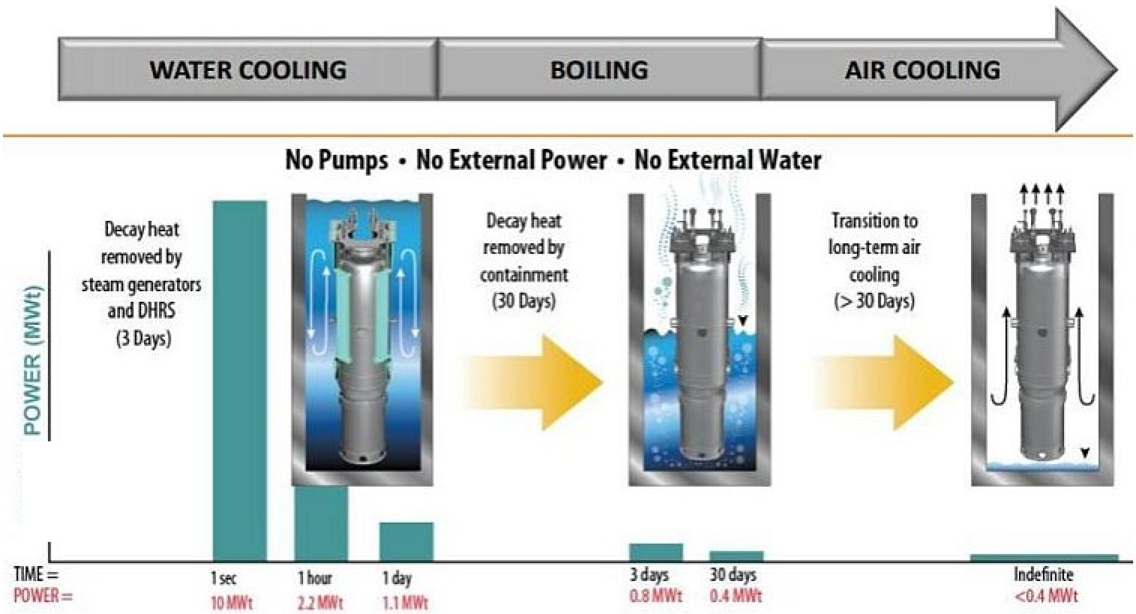

Figure 3.6 NuScale water pool phases during accidents

3.3 Other concepts

In the context of passive safety systems, ELSMOR and in particular WP3.1 /MOR 20/, also present the SMART and the IRIS SMR concepts. While they indeed share features that are investigated in the project, including passive systems to depressurise the containment, their containments are rather comparable to the design of traditional reactors: they do not foresee

[3] www.energyglobalnews.com/nuscale-to-explore-smr-deployment-in-jordan/

novel features related to placing the containment in a water pool and using this feature for residual heat removal. For this reason, they are not considered in this PIRT. However, several concepts exist that realise features similar to NuScale and NUWARD. They are mentioned hereafter for information purposes /IAE 20/.

- CAP200 (SNERDI/SPIC, China)

The containment of CAP200 is submerged in a water pool. After a steam line break accident or a loss of coolant accident, heat will be transferred from steam in containment to the water pool. The water pool is safety-related and prevents the containment from exceeding the design pressure and temperature following a postulated design basis accident by cooling the outside surface of containment, as shown in the above figure. The inventory in the water pool can last at least 7 days after an accident. The passive containment cooling system works without operator control or external assistance.

- DHR400 (CNNC, China)

The DHR400 is designed with inherent safety features. These include a large volume of water in the reactor pool, two sets of reactor shutdown systems, pool water cooling system and a decay heat removal system. With these designs stable long-term core cooling under all conditions can be achieved. The location of the reactor assembly below ground and submerged in 1800 tons of water makes DHR400 highly resistant to external events including aircraft crashes. Additional protection is provided by the reactor building above the pool. At the same time, the design does not include a containment building. While not necessarily required due to the safety of the plant, this could be an issue when licensing the plant outside of China.

- SMR-160 (HOLTEC International, USA)

The SMR-160 conceptual design has been developed by Holtec International as an advanced PWR-type small modular reactor producing power of 525 MW(th) or 160 MW(e) adopting passive safety features. All safety systems are within the containment structure, making them secure and safe from external threats. A large inventory of water within a reservoir outside the containment structure provides long-term post-accident coping, and that structure facilitates air cooling for decay heat removal if the reservoir inventory boils off, for an unlimited coping period.

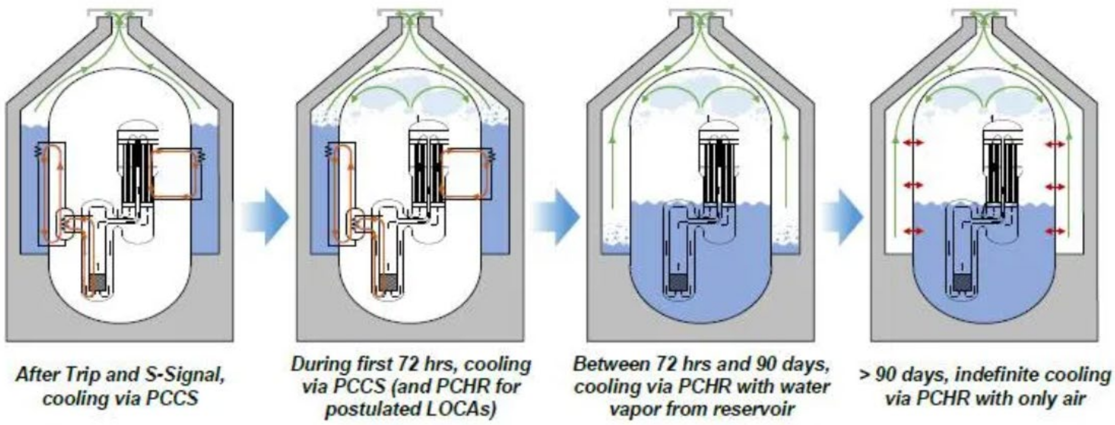

Figure 3.7 HOLTEC water pool phases during accidents

The SMR-160 ICS consists of a free-standing steel containment vessel called the containment structure (CS), supported within a reinforced concrete reactor building called the containment enclosure structure (CES), which also provides missile protection (See Figure 3.7). An annular coolant reservoir (CR) between the CS and the CES is filled with water and serves as the UHS for SMR-160. In addition to preventing the release of radioactive fission products to the environment, the ICS acts as a large passive heat exchanger to cool the core and the spent fuel pool.

4. Description of accident scenarios

Further to the general description of different reactor concepts above, this section is discussing in more detail some safety features of the NUWARD design before sketching how the LOCA and SBO accident scenarios would evolve.

4.1 NUWARD safety systems

4.1.1 Passive heat removal system

The PHRS is made up of 3 sequential natural convection loops linked by heat exchange (cf. Figure 3.3, page 5). To transport the residual heat out of the core it is necessary that the natural convection is taking place as designed, which is intrinsically linked to the heat transfer between the loops.

In particular, the systems are:

- The integrated primary loop. During an accident the MCPs (Main Coolant Pumps) will open a flow path that allows natural convection, driven by the heating of the coolant in the core, its raising towards the upper plenum, its disposing of heat and cooling down in the plate-type S-CSG, and its circulation through the lower plenum back into the core. Phenomena of interest are heat transfers in the core and in the SG, and the natural convection in the proposed core/RPV geometry. It is also important to define the water level required to maintain natural convection, and the influence of pressure drop on the convection and heat transfer. The coolant is light water.

- The intermediate loop that connects the S-CSG with a condenser placed within the containment. Pressure drops in the loop, as well as the driving height difference of S-CSG and condenser, define the natural convection and have a large impact on heat transfer to and from the loop.

- The outer loop. This loop connects the condenser with the water wall outside the containment. Again, the design of the condenser, the pressure drops in the loop, and the driving height difference of the in- and outlet in the water pool define the heat removal capacity of the loop. In addition, the water level in the pool determines whether the outer loop is functional.

Other key questions on the system are related to its starting-up automatically, to the danger of steam cushions and other flow blockages, and to the degree of the loops' filling necessary for its functioning.

4.1.2 Water injection system (low or high pressure)

Given that DBC are considered, it is assumed that a safety injection system will work properly. The boundary conditions of the system – i.e. pressure, water temperature, injection point, possibly filling level of the RPV – can be important for the functioning of the PHRS.

4.1.3 Pressure management of the containment

A LOCA (and any other accident creating a path between RPV and containment) will pressurise the containment, potentially putting at risk its integrity. Protecting mechanisms taking credit of in the design are the presence only of pipes < 30 mm diameter that imply that only small break LOCAs can happen, and the condensing capacity of the containment wall that is on its outside in contact with a cold water-pool.

4.2 NUWARD scenarios

Safety features of the NUWARD design for DBC, but also for DEC A and DEC B situations, have been discussed in Section 3. They will be taken credit for in the system response to different initiating events and in the different accident scenarios that can be postulated for the reactor.

Challenges to safety that come from the reactor are related to nuclear criticality (not further discussed here), the residual heat source, and the high pressure and temperature in the primary circuit.

This section is structuring the view of the safety features along classes of scenarios rather than starting from a large number of individual scenarios. This seems advisable, because the number of key measures and systems applied in the different scenarios is small. Also, with this PIRT focussing on the containment safety functions, it is proposed to acknowledge that accident scenarios can be structured in phases featuring typical phenomena, and to focus on accident phases/phenomena that are related to the containment safety function.

4.2.1 LOCA scenario

According to design objectives, the small diameter of a LOCA and the presence of a passive heat removal system lead to a limitation of the water loss during the LOCA accident. A set of 2 redundant low-pressure safety injection accumulators provides the make-up of water inventory inside the vessel for 3 days. In the longer term (after 3 days), an active system provides the vessel make-up (~10^{m3}/day) from recirculation of water located on the bottom of the containment.

The steel containment is passively cooled by the surrounding pool which ensures the heat removal function for 7 days with no need for a further external heat sink, The steel containment submerged in the pool contributes to the confinement function (3rd barrier); it is protected against small DBC hydrogen leaks by recombiners.

According to the design description, it is understood that the LOCA can be split into several phases, considering not only DBC but also DEC. The latter assuming additional failure of active safety injection systems:

During the **first phase (DBC)**, the operation of the passive heat removal system firstly allows to drop the primary pressure inside the vessel and secondly allows to remove the heat from the core to the waterwall; once the pressure set point of the low-pressure safety accumulators has been reached, water lost through the break and evaporation is made up by these accumulators. The PHRS continues functioning and ensures heat removal from the core. The containment is pressurised to a pressure that is a function of the steam released from the break and the condensation on surfaces in the containment. Water lost through the break is collected in the containment and would play part in natural convection processes.

The **second phase** is entered upon the exhaustion of the passive accumulators. By this time, the effectiveness of the PHRS will deteriorate, the core will uncover, and core damage will occur. Typical further phenomena of this evolution would be RPV dry-out and core melting. It is important to stress that this is the qualitative description of the scenario and has not been quantified within ELSMOR.

During this accident phase, the containment cooling function remains unchanged and limits the containment pressure.

The **third phase** of the accident (DEC-B situation) would be In-Vessel Retention of a melt pool in the lower plenum of the RPV, with flooding of the reactor pit a key action to invoke this strategy. During this phase, heat is removed through the RPV wall to the reactor pit, and from there through the containment atmosphere to the containment wall. Like in the second phase, the containment cooling function would be key to pass the heat to the water wall as heat sink.

It is clear that the containment cooling function plays an important role during all phases of the LOCA. During the grace period of 7 days the water wall as ultimate heat sink is ensured. For the present PIRT, advice was given that the loss of the water wall, and thus accident phases beyond the three phases described should not be considered.

During the second and third phase, the containment cooling is the only mechanism of removing residual heat from the damaged core. The success of this heat removal mechanism depends strongly on the level of heat generation and thus on the fuel burn-up of the core and the length of the grace period.

4.2.2 SBO scenario

An SBO (e.g. following an earthquake) would be one of the most challenging accident scenarios in particular when assuming that the availability of diesel generators is impacted. Batteries are credited with providing some DC power for a limited number of hours.

The F-SMR has been designed with the goal of offering a 3-day grace period without external supply requirement for an SBO scenario. This is owing to the PHRS that consists of two redundant safety SGs that dispose of their heat to a safety condenser placed in the containment and using the water wall as UHS.

In the event of an SBO scenario, several main phases can be distinguished:

In the **first phase**, the PHRS will work as designed and will suffice to remove residual heat and limit the heating-up of the core. This passive loop has been a subject of the PIRT in ELSMOR WP3. The heat disposed of in the water wall will cause evaporation and will diminish the UHS water volume. Unless this volume loss is made up until the end of the 7-day grace period, the SACO secondary side will at some point in time dry out. Assuming that the PHRS manages to remove the residual heat of the primary circuit during this accident phase implies that the containment heat removal function will not come into action.

Drying-out of the water wall as PHRS heat sink would mark the begin of a **second phase** with a failed PHRS, which would lead to the heating up of the core, primary pressurisation, the opening of safety valves and blowing-off of steam. Passive accumulators, activating at a low pressure set-point, would delay the dry-out of the core. However, the assumption of an exhausted water wall would mean that the containment heat removal would not be available, and that the small containment could eventually fail.

4.2.3 Other initiating events

Other initiating events have not been considered.

4.3 NuScale safety systems

According to the facility description, several systems can be distinguished. The following descriptions are taken form /IAE 20/ and the Advanced Reactors Information System (ARIS) database at IAEA [4]..

4.3.1 Decay Heat Removal System

According to the facility description several systems can be distinguished:

"The DHRS, a passive engineered safety feature, transfers decay heat from the reactor to the reactor pool via the steam generators. The DHRS provides cooling during transients and accidents that result in a loss of normal feedwater. It has two independent trains, each capable of sufficient heat transfer to prevent potential fuel damage. The decay heat removal heat exchanger (DHRHX) is submerged in the reactor pool. The inlet to the DHRS is connected to the main steam line. Valves at the exit of the DHRHX automatically open to actuate the system to return condensate back to the steam generator feedwater header. Steam produced in the steam generators is condensed in the DHRHX and the condensate returns to the inlet of the steam generator in a closed loop mode of operation. For DHRS operation without a LOCA or opening of the RVVs, similar to normal operation, the primary coolant is cooled by convection heat transfer as it flows over the steam generator tubes. The steam generator removes heat from the reactor coolant in the reactor vessel annulus, creating a density difference between the hotter, lower-density coolant inside the riser and the cooler, higher-density coolant in the downcomer. This density difference causes natural circulation of the reactor coolant in the same manner as during normal operation, but at a reduced flow rate. For DHRS operation with a LOCA or following actuation of the RVVs, the RCS inventory is reduced, and the primary coolant is cooled initially by convection and then later by condensation on the steam generator tubes. The condensate flows downward and returns to the reactor vessel lower plenum for cooling the core."

4.3.2 Containment Heat Removal System

"Following a postulated break in the primary or secondary systems or an actuation of the RVVs, steam released into the evacuated containment vessel is condensed on the inside surface of the containment vessel. The containment heat removal system (CHRS) then transfers the energy to the reactor building pool by conduction and convection heat transfer modes. The CHRS, a passive engineered safety feature, consists of the reactor building pool and the evacuated containment vessel which enhances condensation. The reactor building pool consists of a large, below-grade stainless steel lined concrete pool that is designed to provide cooling of the containment vessels for at least 72 hours following any design basis event without any active heat removal from the pool. Following a postulated break in the primary or secondary systems, steam released into the containment would be condensed on the inside surface of the containment vessel, which is cooled by conduction and convection heat transfer to the reactor building pool."

4.3.3 Emergency Core Cooling System

"The ECCS, an engineered safety feature, consists of two independent RVVs, two independent reactor recirculation valves (RRVs), and the CHRS. The ECCS provides a means of core decay heat removal following a SBLOCA. The ECCS is automatically initiated by the RPS causing the opening of the RVVs to create a release path for the primary coolant to flow into the containment vessel. This release path is in addition to the SBLOCA release path. The primary coolant collects at the bottom of the containment vessel after the steam phase condenses on the containment vessel. After a sufficient depth of water accumulates in the containment vessel the RRVs automatically open. Opening the RRVs creates a flow path for the water in the containment

[4] https://aris.iaea.org/PDF/NuScale-NPM200_2020.pdf

vessel to flow into the downcomer of the reactor vessel. This establishes a natural circulation loop whereby water that is boiled in the core flows up through the RVVs, is condensed and collected in the containment vessel, and is then returned through the RRVs into the downcomer for stable long-term core cooling."

4.4 NUSCALE scenarios

A description of the response of the NuScale design to accident scenarios can be found in Chapter 15 of /NUS 19/. Since the subject to copyright no detailed information can be given in this document. The reader is referred to the documents on the corresponding U.S. NRC webpage[5]. Other sources provide some though more general information /IAE 20/./IAE 20//IAE 20//IAE 20/

4.4.1 LOCA

According to the NUSCALE licensing safety report /NUS 19/ chapter 15: "In conjunction with the containment heat removal function of containment, the ECCS provides a means of core decay heat removal for LOCAs or during loss of both trains of the DHRS, which is a beyond-design-basis-event condition. The DHRS provides an additional capacity to remove decay heat during the initial blowdown period of a LOCA but is not credited in the LOCA model."

"The ECCS is automatically initiated by the RPS causing the opening of the RVVs to create a release path for the primary coolant to flow into the containment vessel. This release path is in addition to the SBLOCA release path. The primary coolant collects at the bottom of the containment vessel after the steam phase condenses on the containment vessel. After a sufficient depth of water accumulates in the containment vessel the RRVs automatically open. Opening the RRVs creates a flow path for the water in the containment vessel to flow into the downcomer of the reactor vessel. This establishes a natural circulation loop whereby water that is boiled in the core flows up through the RVVs, is condensed and collected in the containment vessel, and is then returned through the RRVs into the downcomer for stable long-term core cooling. "

The description shows that in NuScale there is no stage of primary water make-up through passive accumulators – the reactor protection system switches directly to the ECCS and to removing residual heat through the containment wall. Consequently, the LOCA phases 1 and 2 of the NUWARD scenario fall together into one phase in NuScale.

Phase 3 in NUSCALE is similar to NUWARD and would only appear if the water pool as UHS cannot be maintained. Otherwise, the ECCS loop of NuScale is designed to avoid core uncovery /NUS 19/.

4.4.2 SBO

An SBO (Station BlackOut): "causes the MPS to initiate a reactor trip, actuate the DHRS, and close the containment isolation valves. The loss of normal power also causes the loss of the EDSS chargers causing the EDSS to rely on backup batteries. At 24 hours, the MPS load sheds the ECCS valves causing them to open to the fail-safe position; RCS coolant is discharged into containment when the IAB valve operating pressure threshold is reached." See /NUS 19/ chapter 15.0.0.6.2.

The opening of ECCS means opening the RPV and creating a natural convection loop between core as heat source and containment wall immersed in the surrounding water pool as heat sink.

[5] Application Documents For The NuScale Design | NRC.gov

In this way, the SBO scenario in NuScale consists of 2 phases:

In the first phase heat is removed, and primary pressure and temperature controlled, by employing the PHRS. This corresponds to the first scenario phase of NUWARD.

In the second phase, starting at 24 hours, the residual heat is removed by the ECCS loop, as described for the LOCA.

5. Simplified PIRT on thermohydraulic containment safety features

The objective of this task is to elaborate a reduced PIRT to characterize the relevant phenomena for heat removal from the containment with passive safety features as identified in WP 1 and discussed in WP 2. The identification of significant T/H phenomena involved in the behaviour of the SMR should cover normal and accidental conditions considering DBC and DEC conditions. The main result is a PIRT matrix containing relevant phenomena necessarily to be considered to provide a better understanding of the safety functions in the containment, water pools within and outside of the containment and the heat transfer from and to the containment shell. In addition, thermal stratification and local boiling conditions have to be taken into account. The PIRT will provide the basis of further investigations in this WP.

In setting up a PIRT, usually linkages are established in terms of level of knowledge between a process, the experimental evidence, and code application.

The PIRT foreseen within WP4.1 of the ELSMOR project is carried out with the objective of identifying safety analyses methods required for demonstrating the containment safety functions of the SMR concepts under consideration. In particular, the PIRT will focus on thermal-hydraulic phenomena and should provide information required to assess the model basis of candidate codes, taking into account the foreseen or expected boundary conditions.

An important outcome should be the identification and assessment based on expert judgement of both, phenomena or physical processes, their mathematical modelling, and experimental data needed to evaluate the safety function behaviour and gaps still existing and necessarily to be closed in whatever field. This is usually done relative to a specific objective, so called figure of merit (FOM), that is in this case the assurance of containment integrity by keeping its pressure well below design limits. The PIRT not necessarily presents a closed process, rather it is a tool to provide guidance for the subsequent steps /USN 05/.

While ELSMOR is looking at several SMR designs, the PIRT will be applied to the NUWARD and NuScale design, taking into account their specific safety features with view to the water pool as the ultimate heat sink. The safety features related to DBC and DEC have been re-iterated in section 3 above and are the basis for the analyses made and conclusions drawn in this document.

The initial phases of the PIRT process described in this step can rely heavily on expert opinion, which can be subjective. Therefore, it is important to validate the PIRT using experimentation and analysis. That might necessitate a reassessment of the PIRT.

The present PIRT is simplified in several ways, going only as much into detail as merited by limited information available on the SMR concepts, and trying to keep information as concentrated as possible. In particular, the following choices have been made:

1. The PIRT is focussed on the containment's passive heat removal safety function, i.e. the removal of residual heat from the core through RPV and containment to a "water wall" directly in contact with the outer containment surface.

2. Care has been taken to identify all physical phenomena that play a role in the containment's passive heat removal safety function.

3. While significant design differences exist between NUWARD and NuScale, is has been found that the phenomena of the PIRT are almost the same, giving rise to covering both concepts in the same PIRT tables.
   There is an exemption for the tertiary side of the PHRS; the related phenomena linked to only one of the concepts are clearly marked in the tables.
   A risk of this approach is that the ranking will not be able to point out a phenomenon that is of different importance in the two concepts. However, this has been accepted in the interest of avoiding a complexity that is not warranted by limited description of the designs available.

4. PIRT tables have been created for a SBO and for a LOCA scenario that pose different initial/boundary conditions to the containment heat removal safety function. These scenarios are described in the section below, based on the understanding of the authors of the available system descriptions.

5. The importance of phenomena contributing to the containment safety function is typically linked to the different phases of the accident progression. These phases are invoked in the scenario descriptions below and they are referenced when describing the phenomena in the PIRT tables. However, for the sake of simplicity and acknowledging the fact of limited published information, the phenomena are ranked for their overall importance rather than for their importance during the individual phases.

Finally, some remarks are due on the appearance of the PIRT:

1. The objective of assessing the model basis of candidate codes for analyses to be carried out in several other sub-work-packages of ELSMOR WP4 has been the reason for diverging from other PIRTs: the contributors were asked to rank three aspects of knowledge (physics; experimental; model basis and validation) and the overall importance of the different phenomena.

2. Screening parameters' relative relevance and relative dispersion have been calculated and are displayed in the tables. They are based on the importance ranking and on the ranking of the knowledge level in the model basis and validation.

5.1 PIRT tables elaborated

The two separate PIRTs developed for the phases of the considered accidents (high-pressure SBO and low-pressure LOCA) gather the identified phenomena for the initial phase and the long-term phase. The latter also includes those thermal-hydraulic phenomena that usually occur during the severe accident phase with core degradation. These phenomena reflect the complexity of the different phases and the close coupling of primary circuit with the containment and the UHS. Based on the PIRTs, the several unique phenomena are identified that are of high importance and/or low knowledge level, and thus of primary interest for further research. The initially made division into NUWARD and NuScale on the one hand and SBO and LOCA on the other hand will only be kept for the scenarios. The main reason is that while a clear separation can be done for the scenarios and the phenomena and safety features for the scenarios this cannot be supported for the two designs under consideration. As already stated, the lack of detailed information is the key to be kept in mind. For the time being both designs will be treated commonly. Given that more information on the performance and technical details of the safety features will be made available in the future, a review and update of the PIRT is strongly recommended.

The complete tables are provided at the end of the report in Table 7 and Table 8.They consist of

- The list of phenomena, for each scenario, that has been elaborated by systematically analysing the physical processes that contribute to the removal path of heat from the core through the containment and to the water pool surrounding the containment. The columns C, E and F covering (i) the "containment safety system", (ii) the "macroscopic behaviour" and (iii) the "microscopic phenomena" describe each phenomenon. In addition, the column D describes at which phase of the accident scenario the phenomenon is active.
  This list was proposed by the authors and was then discussed and finalised together with the participants contributing to the task.

- The columns G-K, M-Q and S-W provide the space for ranking the three different knowledge areas "physical phenomena", "experimental evidence" and "model basis and validation", respectively. The columns Y-AC provides the space for the importance ranking. Each ranking of knowledge and importance levels could be commented by the partners in their table to offer their understanding of that phenomenon – these multiple comments are not offered in the overall table, though. The ranking itself is further described in the section below.

- In the columns AE and AF, the screening parameters as defined in the section below.

5.2 Phenomena ranking

The tables with the completed set of phenomena was distributed to the partners contributing to the PIRT exercise. Several points need to be made about the ranking process:

- Late in the project it was decided to count the vote of every expert taking part in the exercise rather than just one vote per participating institution. The number of experts were:

  - LEI (Lithuania) 2
  - GRS (Germany) 2
  - JRC (EC) 1
  - POLIMI and ENEA (Italy) 3

- At this time, LEI had already submitted its ranking that had been carried out by two experts who had agreed on every single ranking value. Rather than repeating the exercise, LEI was asked to weight its table with the no. of experts. All other ranking was made by individuals and then combined such that one set of tables was submitted per partner.

- It is also important to note that some experts decided not to vote on some of the phenomena. In this case, the ensemble of rankings is smaller than the total of 8 experts participating. The reasons given for not ranking certain items will be described below. The procedure is similar to the one followed in WP3.1 for the PIRT on safety core cooling. It is briefly explained for information purposes.

Table 1. Evaluation scale used in the PIRT analysis

Rank	Weight	Definition with respect to the knowledge	Definition with respect to the importance
High (H)	1.0	The phenomenon is well known and understood. Experimental data is available. Models are validated.	The phenomenon is judged important according to the evaluation criteria
Medium (M)	0.5	The phenomenon is partially known and understood. Experimental data is available but in small quantity / quality.	The phenomenon is judged moderately important according to the evaluation criteria.
Low (L)	0.0	The phenomenon is poorly known and understood. Little or no experimental data is available. No validated models.	The phenomenon is judged of little or no importance according to the evaluation criteria.

The participants of the exercise have ranked the knowledge and importance levels of the different phenomena according to Table 1; the overall ranking has then been calculated as the weighted average

$$Knowledge\ level \stackrel{\text{def}}{=} \text{KL} \stackrel{\text{def}}{=} \frac{0.0\, n_L + 0.5\, n_M + 1.0\, n_H}{n_L + n_M + n_H}$$

where n_L, n_M and n_H represent the number of 'low', 'medium' and 'high' votes assigned to the particular knowledge aspect (physical, experimental, modelling) of the phenomenon, and

$$Importance\ level \stackrel{\text{def}}{=} \text{IL} \stackrel{\text{def}}{=} \frac{0.0\, n_L + 0.5\, n_M + 1.0\, n_H}{n_L + n_M + n_H}$$

where n_L, n_M and n_H represent the number of 'low', 'medium' and 'high' votes assigned to its importance. The PIRT tables show the added-up scores that assume a value between 0 and 1 and add a colour spectrum to highlight the overall level ranking, see Table 2:

- Knowledge: red (no knowledge: 0) – yellow – green (complete knowledge: 1)
- Importance: green (low importance: 0) – yellow – red (high importance: 1)

For the overall PIRT evaluation, the 3 knowledge categories (physical, experimental, modelling) have been averaged by adding all low, medium and high-level rankings and calculating the ranking as described above, over all partners and all knowledge categories. As an example, the overall knowledge ranking numbers for phenomenon 10 in the LOCA is [0, 3, 2] + [0, 5, 0] + [2, 3, 0] = [2, 11, 2], leading to a knowledge level of 0.5. This example is the first line of Table 3 that takes its values from the LOCA PIRT Table 7.

Table 2. Example of the ranking display.

Level of knowledge	Ranking Low /Med /High			Level	…	Importance Ranking Low /Med /High			Level
Experimental evidence (facility, scaling, availability)	L	M	H		…	L	M	H	
	0	1	4	0.900	…	0	5	0	0.500
	2	5	1	0.438	…	0	1	7	0.938

Following the example of PIRT WP3 /MOR 20/, a methodology of two screening parameters /OEC 18/ has been used for providing a quick overview of the PIRTs results: the *relative relevance* and the *relative dispersion.* The *relative relevance*, referred to a phenomenon α has been defined as follows:

$$relative\ relevance_{\alpha} \stackrel{\text{def}}{=} \frac{\mathrm{IL}_{\alpha}\,(1-\mathrm{KL}_{\alpha})}{\max\limits_{\alpha}\ [\mathrm{IL}_{\alpha}\,(1-\mathrm{KL}_{\alpha})\,]}$$

where IL_{α} and KL_{α} are the importance level and the knowledge level, respectively, of the phenomenon α. The denominator represents the maximum value of the product $\mathrm{IL}_{\alpha}\,(1-\mathrm{KL}_{\alpha})$ among all the phenomena. The phenomena having the largest values of relative relevance are those on which further research should be conducted primarily: they are more important and less known than lower scoring phenomena.

The *relative dispersion* of a phenomenon α can be defined as follows:

$$relative\ dispersion_{\alpha} \stackrel{\text{def}}{=} \frac{\sigma(\mathrm{IL}_{\alpha})\,\sigma(\mathrm{KL}_{\alpha})}{\max\limits_{\alpha}\ [\sigma(\mathrm{IL}_{\alpha})\,\sigma(\mathrm{KL}_{\alpha})\,]}$$

where $\sigma(\mathrm{IL}_{\alpha})$ and $\sigma(\mathrm{KL}_{\alpha})$ are the standard deviations on the importance level and the knowledge level, and defined as

$$Standard\ deviation\ on\ knowledge \stackrel{\text{def}}{=} \sigma(\mathrm{KL}) \stackrel{\text{def}}{=} \sqrt{\frac{n_L(0.0-\mathrm{KL})^2 + n_M(0.5-\mathrm{KL}\,)^2 + n_H(1.0-\mathrm{KL})^2}{n_L+n_M+n_H-1}}$$

$$Standard\ deviation\ on\ importance \stackrel{\text{def}}{=} \sigma(\mathrm{IL}) \stackrel{\text{def}}{=} \sqrt{\frac{n_L(0.0-\mathrm{IL})^2 + n_M(0.5-\mathrm{IL}\,)^2 + n_H(1.0-\mathrm{IL})^2}{n_L+n_M+n_H-1}}$$

The denominator in the relative dispersion definition represents the maximum value of the product $\sigma(\mathrm{IL}_{\alpha})\,\sigma(\mathrm{KL}_{\alpha})$ among all the phenomena and all the time phases. The phenomena having the largest values of relative dispersion are those on which the members of the workgroup agreed less when they had to rank them. The definition also means that in cases where either $\sigma(\mathrm{IL}_{\alpha})$ or $\sigma(\mathrm{KL}_{\alpha})$ is zero (i.e. unanimity in the ranking), the dispersion value will be zero independent of the standard deviation of the other ranking.

The two screening parameters have been placed in the right -hand side of the PIRTs. The colour legend adopted for them is the same as for the importance level, so the phenomena having the highest relative relevance and/or dispersion are highlighted in red.

For the screening parameters it should be noted that they will be used in the current situation more like an indicating tool than a decision tool. Main reasons are that (i) the number of participants to the ranking exercise is as small as 4; and, (ii) the number of phenomena in the PIRT is small enough to be scanned without much effort.

5.3 Results

For a quicker overview of the results, the tables have been sorted by the relative relevance of phenomena regarding the overall knowledge and importance levels, and results tables created that show the phenomenon number together with ranking values that enter the computation of relative relevance and relative divergence, see e.g. Table 3.

Please note that some phenomena have been ranked by less than the total number of participants. Votes add up to a maximum of 8 in the importance ranking, and to a maximum of 3 x 8 = 24 in the overall knowledge ranking.

A coding is used in the sections below to allow short referencing of phenomena whereas:

- LPi denotes the ith phenomenon in the complete LOCA PIRT (Table 7, p. 26),
- SP*i* refers to the *i*th phenomenon in the complete SBO PIRT (Table 8, p. 27).

5.3.1 LOCA

The full result of the ranking is provided in Table 7 in the appendix. Table 3 is the sorted subset of the overall table comprising the phenomena with a relative relevance above 0.5. According to this, the most significant knowledge gaps are expected in

- the heat transfer from the containment atmosphere to the containment wall under condensation (LOCA Phenomenon (LP) 10); only 5 of 8 experts ranked this phenomenon,
- the heat transfer from the inside the RPV through the RPV wall after melt relocation (LP7),
- the heat transfer to the water pool along the containment outer wall, under boiling conditions (LP13),
- the flow field in the water pool (LP14),
- the water level of the water pool due to evaporation (P16),
- the evaporation-dominated heat transfer at the surface of the water pool given the possibility of thermal stratification in the pool (LP11), and
- heat transfer from water pool to outer building structure (LP15).

Table 3: LOCA phenomena ordered in terms of their relative relevance

LOCA	Overall Knowledge Ranking			Level	Importance Ranking			Level	Rel. relevance	Rel. dispersion
Phenom.	L	M	H		L	M	H			
10	2	11	2	0.500	0	1	4	0.900	1.000	0.328
7	2	19	3	0.521	0	2	6	0.875	0.932	0.295
13	3	13	8	0.604	0	1	7	0.938	0.825	0.319
14	11	13	0	0.271	0	8	0	0.500	0.810	0.000
16	4	12	8	0.583	1	3	4	0.688	0.637	0.717
11	5	8	11	0.625	1	3	4	0.688	0.573	0.811
15	2	10	3	0.533	2	4	2	0.500	0.519	0.616

On LP10, the experts recognised that the small-scale physics are well known, but that the scaling to the reactor-size containment implies local variations that are challenging; that some experiments relevant for this application exist. While models within SA codes (here: the containment module of AC^2) and in CFD codes exist, the detailed ranking in Table 7 shows that experts rated the modelling basis 0.3, i.e. between low and medium. While the knowledge level was thus judged medium, the experts attested the phenomenon a high importance for the containment safety function.

The experts judged both LP7 and LP13 similarly regarding their importance and considered the experimental and modelling basis better than for LP10, see Table 7. A good resolution of LP13 can require a finer meshing than is typically available in SA codes. Again, the application to SMR geometries of models validated for other geometries led to a medium knowledge ranking.

LP14 is different from the first 3 phenomena in that the knowledge of local flow fields is ranked less than good, that experiments measuring the flow field are rare for relevant geometries, and that this is the domain of CFD codes – SA codes typically avoid the computational expense of high resolution. Table 7 gives the details of the ranking. The rather low knowledge ranking is somewhat compensated by an importance ranking that is only medium.

It is also interesting to note as a general observation from Table 7 that the level of knowledge of the physical phenomena was judged rather high, with the exemption of LP14. The level of applicable experimental and modelling knowledge is generally judged less positive owing e.g. to scaling needs, a limited number in particular of relevant integral effects experiments. Unsurprisingly, experimental and modelling knowledge rankings are generally strongly correlated.

It is worth noting that partners' judgement diverged most on LP11, LP16 and LP15.

5.3.2 SBO

The full result of the ranking is provided in Table 8, in the appendix (page 27).

In this evaluation it is important to note that the overall SBO PIRT table has been cut into the 3 parts that are also clearly marked in Table 8:

(i) the phenomena applying to both NUWARD and NUSCALE, SP1 to SP14;

(ii) the phenomena related to the tertiary PHRS side of NUWARD, SP15 to SP20; and,

(iii) the phenomena related to the tertiary PHRS side of NUSCALE, SP21 to SP24. The screening parameters have been calculated separately for the 3 parts of the table.

Table 4 is the sorted subset of the concept-independent part of the table comprising the phenomena with a relative relevance above 0.5. According to this, the most significant modelling gaps are expected in

- the heat transfer from the inside the RPV through the RPV wall after melt relocation (SBO Phenomenon (SP) 4),
- flow field in the water pool (SP11),
- the heat transfer from the containment atmosphere to the containment wall under condensation (SP7); only 5 of 8 experts ranked this phenomenon,
- the heat transfer to the water pool along the containment outer wall, under boiling conditions (SP10)
- water level in water pool, again driven by evaporation (SP14), and
- the evaporation-dominated heat transfer at the surface of the water pool given the possibility of thermal stratification in the pool (SP8).

Table 4: SBO phenomena ordered in terms of their relative relevance

SBO	Overall Knowledge Ranking			Level	Importance Ranking			Level		Rel. relevance	Rel. dispersion
Phenom.	L	M	H		L	M	H				
4	3	18	3	0.500	0	2	6	0.875		1.000	0.393
11	9	12	0	0.286	0	7	1	0.563		0.918	0.298
7	0	13	2	0.567	0	1	4	0.900		0.891	0.262
10	2	13	7	0.614	0	1	7	0.938		0.828	0.360
14	0	15	7	0.659	0	4	4	0.750		0.584	0.424
8	3	10	11	0.667	1	2	5	0.750		0.571	0.882

It is worth noting that partners' judgement diverged most on SP8, as displayed by the relative dispersion parameter.

While there are differences in some votes and SP8, thus the ranking order between SBO and LOCA, it is unsurprising that the same 4 phenomena share the top 4 places and diverge little in terms of the perceived knowledge and importance levels. The detailed discussion above of these 4 phenomena in the LOCA PIRT is applicable to the SBO case.

Table 8 also contains phenomena related to the tertiary side of the PHRS; as the design is different for NUWARD and NuScale, the table distinguishes between the two concepts. It is important to note that extending the PIRT to the PHRS tertiary side does not have unanimous support between the partners in this PIRT – POLIMI/ENEA point out that is has been part of the PIRT that was carried out in WP3 under their responsibility.

The argument that has led to these phenomena still being considered in this containment heat removal PIRT is the fact that the water pool serves as UHS both to the PHRS and to the containment heat removal safety function described in this report, thus creating a dependence of the two safety functions.

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Table 5: SBO phenomena for NUWARD tertiary side ordered in terms of their relative relevance

SBO	Overall Knowledge Ranking			Level	Importance Ranking			Level	Rel. relevance	Rel. dispersion
Phenom.	L	M	H		L	M	H			
19	3	9	1	0.423	0	0	5	1.000	1.000	0.000
18	3	8	2	0.462	0	1	4	0.900	0.840	0.455
17	3	8	2	0.462	1	1	3	0.700	0.653	0.910
20	4	8	3	0.467	1	1	3	0.700	0.647	1.000
16	2	6	5	0.615	0	1	4	0.900	0.600	0.515

Table 5 is the sorted subset of the NUWARD-focussed part of Table 8, comprising the phenomena with a relative relevance above 0.5. According to this, the most significant modelling gaps are expected in

- the onset of natural convection in the tertiary side (SP19)
- the performance under different boundary conditions (SP18)
- the pressure loss (SP17),
- the influence of the type of heat exchanger / condenser (SP20), and
- the single-phase vs. two-phase flow dynamics (SP16).

The divergence of expert opinion on SP20 and SP17 is significant.

Finally, Table 6 is the sorted subset of the NuScale-focussed part of Table 8, comprising the phenomena with a relative relevance above 0.5. According to this, the most significant knowledge gaps are expected in

- performance of SACO under different wetting conditions in an only partly flooded water pool (SP24)
- flow phenomena on the pool side of the SACO (SP22)
- internal flow phenomena in the SACO (SP23), and
- the onset of natural convection in the SACO cooling circuit (SP25).

Table 6: SBO phenomena for NuScale tertiary side ordered in terms of their relative relevance

SBO	Overall Knowledge Ranking			Level	Importance Ranking			Level	Rel. relevance	Rel. dispersion
Phenom.	L	M	H		L	M	H			
24	7	5	3	0.367	0	0	5	1.000	1.000	0.000
22	7	5	3	0.367	0	2	3	0.800	0.800	0.747
23	4	7	4	0.500	0	1	4	0.900	0.711	0.577
25	3	9	3	0.500	1	1	3	0.700	0.553	1.000

The divergence of expert opinion on SP25 is significant.

5.3.3 Experts' comments

During the ranking exercise, experts were given the opportunity to provide comments, in their organisation's PIRT table, on the phenomena they were ranking. Since some of these comments can give valuable background information and insights into the expert knowledge tapped, these comments have been collected in the two additional Tables Table 9 and Table 10 in the appendix. Please note that there has been no selection or redaction of the comments.

6. Summary

As part of Work Package 4 of the EU-ELSMOR project, the elaboration of a PIRT with focus on relevant phenomena identified as being of importance regarding containment safety functions has been executed. The objective of this task is to elaborate a reduced PIRT to characterize the relevant phenomena for heat removal from the containment with passive safety features.

An important outcome is the identification and assessment of phenomena or physical processes, their mathematical modelling, as well as the experimental data needed to evaluate the safety function behaviour and gaps still existing and necessary to be closed in whatever field. This is done relative to a specific objective, so called Figure Of Merit (FOM) that is in this case the assurance of containment integrity by keeping its pressure well below plant specific design limits.

The main result is a matrix containing relevant phenomena necessarily to be considered to provide a better understanding of the safety functions in the containment, water pools within and outside of the containment and the heat transfer from and to the containment shell. In addition, thermal stratification and local boiling conditions must be taken into account. The PIRT will also provide basic information for further investigations in this WP. This concerns in particular the selection of an experiment or an academic test case, where selected codes can be benchmarked.

The usually followed approach in elaborating such PIRT was impaired by the fact that no detailed information is available for the corresponding plant designs concerning data, progression of incidents and accidents and accident management measures to be applied. This renders difficult the identification of phenomena connected to the accident progression. For the time being, it was discussed and agreed between the contributing parties to modify the procedure in terms of identifying weak points in physical understanding, mathematical modelling, and experimental data to support the first two points and to provide information to the others task of WP4. This procedure seems to be reasonable considering the lack of data for the plant designs chosen for the PIRT. Two concepts were identified as being of interest with view to a submerged containment as the ultimate heat sink for decay heat removal. In compliance with the ELSMOR project the French NUWARD concept was the obvious choice. In addition, the NuScale concept was chosen since it is in an advanced state and recently received design certification approval from the U.S. NRC.

The identification and ranking of phenomena were done by 4 partners form 3 countries plus JRC as the European Commission's knowledge and science service. In total 10 experts specialising in different technical areas took part. It was agreed to split the PIRT into two separate tables, distinguishing two classical accident sequences, i.e. LOCA and SBO. Each sequence itself could have been split into different phases, where for each phase main phenomena of importance and the relevance would be screened and ranked. However, since the information on both the plant design and the progress of the sequence is limited, this would introduce more uncertainty and might lead to false conclusions. As a consequence, the phases are only mentioned, but not considered in detail. It is recommended to review the PIRT subject to these conditions as soon as more data is available.

While for the LOCA PIRT, no differentiation was done for the two concepts, it was decided by the panel to subdivide the SBO PIRT into the 3 parts corresponding to phenomena common to both concepts, to NUWARD only or to NuScale. This was necessary, since for the tertiary loop for the heat removal to the UHS (i.e. the water pool) the designs differ considerably.

The main statements can be summarized as follows. With view to the LOCA, one could have expected that the water pool is the main source of uncertainty. However, according to the voting heat transfer processes in the containment seem to be of equal importance in terms of uncertainties existing and influence on safety margin. This concerns heat transfer phenomena at structures (reactor pressure vessel and containment. Phenomena connected to the water pool (boiling, flow field, evaporation) were identified as being a topic for further investigations, but were assessed as being of lightly minor relevance

As concerns the SBO, the assessment has been split as written above. Here, for both concepts, highest relevance was seen for the late phase of an accident with core degradation. This is obvious since this phase is still afflicted with large uncertainties, even in power reactors of the current generation (Gen II, Gen III, III+). However, all other highly ranked phenomena are connected to the water wall, similar to the LOCA assessment.

Looking at the differences in the tertiary loop connected to the water pool, as a matter of fact the SACO realised in the NuScale design was identified as being of high relevance, since its working is crucial for the heat transfer and less knowledge is available in terms of the design and the specific phenomena connected to the fluid flow conditions in the condenser.

For NUWARD, boundary conditions and fluid flow conditions as well as the heat exchanger performance and designs contribute mostly to the relevance. Cleary, the lack of data for NUWARD design makes it difficult to make a clear opinion. This has to be kept in mind, when judging the PIRT results.

The authors strongly recommend reviewing the PIRT as soon as precise information is available.

Appendix

Table 7: Phenomena Identification and Ranking Table for LOCA

LOCA		Containment safety system	Phase	Description of macroscopic behaviour	microscopic phenomena	Knowledge Ranking			Level	Knowledge Ranking			Level	Knowledge Ranking			Level	Importance Ranking			Level	Rel. relevance	Rel. dispersion
Comment		Component e. g. RRC, water pool				Physical phenomena				Experimental evidence (facility, scaling, availability)				Model basis and validation (general or code specific)									
						L	M	H		L	M	H		L	M	H		L	M	H			
1	applicable to both NUWARD - NUSCALE	Containment vessel (internal)	initial phase (blow down)	pressure build-up	inital critical outflow, one phase flow (water)	0	1	4	0.900	0	1	4	0.900	0	1	4	0.900	0	5	0	0.500	0.079	0.000
2		Containment vessel (internal)	intermediate	pressure build-up	two-phase flow (water-steam) condensation / evaporation	0	2	6	0.875	0	2	6	0.875	0	3	5	0.813	1	2	5	0.750	0.223	0.845
3		Containment vessel (internal)	long-term	presssure build-up	one phase flow (steam), condensation	0	2	6	0.875	0	2	6	0.875	0	2	6	0.875	0	4	4	0.750	0.149	0.535
4		Containment vessel (internal)	all phases	water level in containment	one phase flow (steam), volume / wall condensation	0	1	7	0.938	0	3	5	0.813	0	4	4	0.750	1	4	3	0.625	0.248	0.816
5		Containment vessel (internal)	intermediate, long-term	heat transfer, contact area with RPV wall (non isolated?)	heat transfer, 1-phase flow, free convection	0	1	7	0.938	0	3	5	0.813	0	2	6	0.875	5	2	1	0.250	0.050	0.756
6		Containment vessel (internal)	long-term	heat transfer, contact area with RPV wall before melt relocation	heat transfer, 2 phase flow under boiling conditions	0	2	6	0.875	1	3	4	0.688	1	6	1	0.500	1	3	4	0.688	0.546	0.859
7		Containment vessel (internal)	late phase (SA)	heat transfer, contact area with RPV wall after melt relocation	heat transfer, free convection 2 phase flow under boiling conditions	0	5	3	0.688	1	7	0	0.438	1	7	0	0.438	0	2	6	0.875	0.781	0.354
8		Containment Vessel (internal)	all phases	Atmospheric composition, stratification (e. g. NC, steam)	heat transfer, condensation, buoyancy	0	4	4	0.750	0	3	5	0.813	0	4	4	0.750	1	4	3	0.625	0.248	0.816
9		Containment vessel (inner wall)	all phases	heat transfer, water contact area with containment wall	water pool level, free convection	0	2	3	0.800	0	3	2	0.700	0	4	1	0.600	2	2	1	0.400	0.254	0.808
10		Containment vessel (inner wall)	all phases	heat transfer, atmosphere contact area with containment wall	wall area, condensation, rivulets, wetted area	0	3	2	0.700	0	5	0	0.500	2	3	0	0.300	0	1	4	0.900	1.000	0.529
11		Submerged containment water pool (outer surface)	all phases	Heat transfer at water surface (evaporation)	Thermal stratification	0	1	7	0.938	1	3	4	0.688	4	4	0	0.250	1	3	4	0.688	0.818	0.859
12		Submerged containment outer wall	early phase	Heat transfer along cont. wall, (single phase)	natural convection thermal stratification (water level)	0	2	6	0.875	2	5	1	0.438	1	6	1	0.500	1	5	2	0.563	0.446	0.740
13		Submerged containment outer wall	aearly/late phase	Heat transfer along wall, (boiling conditions)	natural convection thermal stratification (water level)	0	2	6	0.875	2	5	1	0.438	1	6	1	0.500	0	1	7	0.938	0.744	0.408
14		Submerged containment water pool	all phases	flow field in water pool	3-D effects, symmetric vs. non-symmetric	3	5	0	0.313	5	3	0	0.188	3	5	0	0.313	0	8	0	0.500	0.546	0.000
15		Submerged containment water pool	all phases	heat transfer from water pool to outer building structure	free convection, stratification	0	3	2	0.700	2	2	1	0.400	0	5	0	0.500	2	4	2	0.500	0.397	0.000
16		Submerged containment water pool	late phase	water level	evaporation of water pool	0	1	7	0.938	2	5	1	0.438	2	6	0	0.375	1	3	4	0.688	0.682	0.744
17		Submerged containment water pool	early phase	onset of natural convection	buoyancy, initial & boundary conditions, density differences, geometry unknown	0	2	3	0.800	2	2	1	0.400	1	4	0	0.400	5	0	3	0.375	0.357	1.000

Table 8: Phenomena Identification and Ranking Table for SBO

SBO		Containment safety system	phase	Description of macroscopic behaviour	microscopic phenomena	Knowledge Ranking			Level	Knowledge Ranking			Level	Knowledge Ranking			Level	Importance Ranking			Level	Rel. relevance	Rel. dispersion
Comment		Component e. g. RRC, water pool				Physical phenomena				Experimental evidence (facility, scaling, availability)				Model basis and validation (general or code specific)									
						L	M	H		L	M	H		L	M	H		L	M	H			
1	applicable to both NUWARD - NUSCALE	Containment vessel (internal)	depressurisation phase	Water accumulation in containment water level	volume/wall condensation	0	1	7	0.938	0	4	4	0.750	0	5	4	0.722	2	3	3	0.563	0.217	0.588
2		Containment vessel (internal)	all phases	heat transfer, contact area with RPV wall	free convection 1-phase vs. 2-phase flow	0	2	6	0.875	0	3	5	0.813	0	2	6	0.875	0	7	1	0.563	0.098	0.219
3		Containment vessel (internal)	late phase	heat transfer, contact area with RPV wall before melt relocation	free convection, 2 phase flow under boiling conditions	0	1	7	0.938	1	3	4	0.688	2	5	1	0.438	1	3	4	0.688	0.537	0.637
4		Containment vessel (internal)	late phase	heat transfer, contact area with RPV wall after melt relaocation	free convection, 2 phase flow under boiling conditions	0	5	3	0.688	1	7	0	0.438	2	6	0	0.375	0	2	6	0.875	0.760	0.286
5		Containment vessel (internal)	all phases	Atmospheric composition, stratification (e. g. NC, steam)	heat transfer, condensation, buoyancy	0	4	4	0.750	0	4	4	0.750	0	4	4	0.750	0	5	3	0.688	0.239	0.370
6		Containment vessel (inner wall)	all phases	heat transfer, water contact area with cont. wall	water level, free convection	0	1	4	0.900	0	3	2	0.700	0	3	2	0.700	4	1	0	0.100	0.042	0.327
7		Containment vessel (inner wall)	all phases	heat transfer, atmoshere contact area with cont. wall	wall area, condensation, rivulets, wetted area	0	4	1	0.600	0	5	0	0.500	0	4	1	0.600	0	1	4	0.900	0.500	0.267
8		Submerged containment water pool (outer surface)	all phases	Heat transfer at water surface (evaporation)	Thermal stratification	0	1	7	0.938	0	4	4	0.750	3	5	0	0.313	1	2	5	0.750	0.716	0.523
9		Submerged containment outer wall	early phase	Heat transfer along cont. wall, natural convection (single phase)	Thermal stratification (water level)	0	2	6	0.875	1	4	1	0.500	1	6	1	0.500	2	4	2	0.500	0.347	0.540
10		Submerged containment outer wall	early/late phase	Heat transfer along wall, natural convection (boiling conditions)	Thermal stratification (water level)	0	3	5	0.813	1	4	1	0.500	1	6	1	0.500	0	1	7	0.938	0.651	0.253
11		Submerged containment water pool	all phases	flow field in water pool	3D- effects symmetric vs. non-symmetric	3	5	0	0.313	3	3	0	0.250	3	4	0	0.286	0	7	1	0.563	0.558	0.253
12		Submerged containment water pool	all phases	heat transfer to outer building	stratification	0	3	2	0.700	0	2	1	0.667	0	5	0	0.500	3	3	2	0.438	0.304	0.000
13		Submerged containment water pool	all phases	heat transfer to outer building structure	stratification	1	2	1	0.500	0	2	1	0.667	1	3	0	0.375	4	1	2	0.357	0.310	0.636
14		Submerged containment water pool (NuScale, NUWARD?)	late phase	water level in water pool	evaporation	0	2	6	0.875	0	5	1	0.583	0	8	0	0.500	0	4	4	0.750	0.521	0.000
15	NUWARD	Submerged containment NUWARD water pool	early phase	Onset of natural convection	initial & boundary conditions, mass flow	0	2	3	0.800	0	2	1	0.667	2	3	0	0.300	7	0	1	0.125	0.122	0.518
16		Piping RRC to water wall, NUWARD	all phases	Flow dynamics single vs. two-phase	turbulent phase-interface friction approaches from heat transfer handbooks applicable for steady	0	3	2	0.700	2	0	1	0.333	0	3	2	0.700	0	1	4	0.900	0.375	0.327
17		Piping RRC to water wall NUWARD	all phases	Pressure loss	frictional drag + local resistences	0	3	2	0.700	2	1	0	0.167	1	4	0	0.400	1	1	3	0.700	0.583	0.535
18		RRC NUWARD	all phases	perfomance under different boundary conditions	one phase / two phase flow	0	3	2	0.700	2	1	0	0.167	1	4	0	0.400	0	1	4	0.900	0.750	0.267
19		RRC NUWARD	all phases	Onset of natural convection	buyoancy initial & boundary conditions, density differences, stratification	1	3	1	0.500	0	3	0	0.500	2	3	0	0.300	0	0	5	1.000	0.972	0.000
20		RRC NUWARD	all phases	influnce of type of heat exchanger / condenser	flow phenomena	0	3	2	0.700	2	3	0	0.300	2	2	1	0.400	1	1	3	0.700	0.583	1.000
21	NUSCALE	Submerged containment NuScale water pool	early phase	Onset of natural convection	initial & boundary conditions, density differences, stratification	1	4	0	0.400	0	5	0	0.500	2	2	1	0.400	1	3	1	0.500	0.417	0.791
22		external SACO NuScale	all phases	flow phenomena	one phase vs. two phase flow	1	2	2	0.600	2	2	1	0.400	4	1	0	0.100	0	2	3	0.800	1.000	0.327
23		external SACO NuScale	all phases	flow phenomena	internal flow,one phase vs. two phase flow boundary cond.	0	3	2	0.700	2	2	1	0.400	2	2	1	0.400	0	1	4	0.900	0.750	0.500
24		external SACO NuScale	late phase	partly flooded pool perfomance of SACO under different wetting conditions	wetting, heat transfer	2	2	1	0.400	2	2	1	0.400	3	1	1	0.300	0	0	5	1.000	0.972	0.000
25		RRP cooling circuit	early phase	Onset of natural convection (NuScale)	buoyancy initial & boundary conditions, density differences, stratification	0	3	2	0.700	1	4	0	0.400	2	2	1	0.400	1	1	3	0.700	0.583	1.000

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Table 9: Comment fields related to the PIRT for a LOCA

LOCA Comment		Containment safety system – Component e. g. RRC, water pool	Phase	Description of macroscopic behaviour	microscopic phenomena
1	applicable to both NUWARD - NUSCALE	Containment vessel (internal)	initial phase (blow down)	pressure build-up	inital critical outflow, one phase flow (water)
2		Containment vessel (internal)	intermediate	pressure build-up	two-phase flow (water-steam) condensation / evaporation
3		Containment vessel (internal)	long-term	presssure build-up	one phase flow (steam), condensation
4		Containment vessel (internal)	all phases	water level in containment	one phase flow (steam), volume / wall condensation
5		Containment vessel (internal)	intermediate, long-term	heat transfer, contact area with RPV wall (non isolated?)	heat transfer, 1-phase flow, free convection
6		Containment vessel (internal)	long-term	heat transfer, contact area with RPV wall before melt relocation	heat transfer, 2 phase flow under boiling conditions
7		Containment vessel (internal)	late phase (SA)	heat transfer, contact area with RPV wall after melt relocation	heat transfer, free convection 2 phase flow under boiling conditions
8		Containment Vessel (internal)	all phases	Atmospheric composition, stratification (e. g. NC, steam)	heat transfer, condensation, buoyancy
9		Containment vessel (inner wall)	all phases	heat transfer, water contact area with containment wall	water pool level, free convection
10		Containment vessel (inner wall)	all phases	heat transfer, atmosphere contact area with containment wall	wall area, condensation, rivulets, wetted area
11		Submerged containment water pool (outer surface)	all phases	Heat transfer at water surface (evaporation)	Thermal stratification
12		Submerged containment outer wall	early phase	Heat transfer along cont. wall, (single phase)	natural convection thermal stratification (water level)
13		Submerged containment outer wall	aearly/late phase	Heat transfer along wall, (boiling conditions)	natural convection thermal stratification (water level)
14		Submerged containment water pool	all phases	flow field in water pool	3-D effects, symmetric vs. non-symmetric
15		Submerged containment water pool	all phases	heat transfer from water pool to outer building structure	free convection, stratification
16		Submerged containment water pool	late phase	water level	evaporation of water pool
17		Submerged containment water pool	early phase	onset of natural convection	buoyancy, initial & boundary conditions, density differences, geometry unknown

Comment	Level of knowledge - physical phenomena: ENEA_POLIMI	GRS	JRC	LEI
1	The physical phenomenon related to pressure buildup are well understood.	critical discharge massflow chocked flow	break flow, p_prim >> p_cont	Physics well understood
2		water entrainment, critial discharge, pressure gradient, chocked flow (important for SBLOCA: defines long term pressure)	break flow, p_prim >= p_cont	Physics well understood
3		critical discharge, chocked flow (important for SBLOCA: defines long term pressure)	break flow, p_prim >= p_cont	Physics well understood
4	The physical phenomenon related towater level are well understood.	condensation, formation of convection loops, drainage along wales, heat conduction through wall, heat profile of the wall structure, stable water film on different surfaces, steam water data	Integral effect	Physics well understood
5	The phenomena of heat transfer and natural circulation one phase flow are well understood.	density differences, heat transfer into the wall, temperatur profile wall, nuselt / reynolds number, water / steam data	HT wall/fluid	Physics well understood
6	The phenomena involved here are well understood (two-phase, boiling, condensation, free convection)	nucleate vs. film boiling, nukiyama curve, radiativ heat transfer, heat conduction (e.g. RPV wall), heat radiation, heat distribution / release from melt inside RPV	HT wall/fluid	Physics well understood
7		nucleate vs. film boiling, nukiyama curve, radiative heat transfer, focussing effect, crust formation, heat conduction	HT wall/fluid, CHF	Physics well understood, local effects are important.
8	The phenomena is known	density distribution, formation of very inhomogenous heat transfer conditions, production of NC gases (oxidation)	Integral effect	Physics well understood in small scale, but integral facility with specific geometry is important
9		density differences, nucleate / film boiling, convections loops in pool (energy transfer on other structures / to atmosphere)	HT wall/fluid	Physics well understood
10	The microscopic phenomena of condensation of flows are well studied in literature.	atmospheric composition above water surface (different heat capacities), inhomogenous heat distribution in wall structures, wall roughness	HT wall/steam atmosphere	Physics well understood. Scaling and film flow issues on high vertical wall.
11	The phenomena is known	gas velocity, denisty differences, humidity, temperatur, formation of convection loops over water surface	Evaporation	Physics well understood
12	The phenomena is known	density differences, reynolds / nusselt number	HT wall/fluid	Physics well understood
13		nucleate vs. film boiling, nukiyama curve, densitiy inhomogeneity nusselt / reynolds number, unless heat flow is very high or water level very low, evaporation should domintae	HT wall/fluid	Physics well understood
14	The phenomena are not well known (strongly dependent on geometry)	density diffrences, heat transfer structure -> water local effect: nucleate / film boling	flow field, integral effect	Specific geometry is important
15		heat tranfer coefficent, radition (surface -> structure), evaporation, condensation, convectiv loops (especially water surface), reynolds number, nusselt number	HT wall/fluid	Specific geometry is important
16	The phenomena of heat and mass transfer is well understood.	gas velocity at pool surface, gas humidity convection in building	Evaporation	Physics well understood
17		density differences, reynolds / nusselt number, gemetrical details	natural convection	Physics well understood

Comment	Level of knowledge - Experimental evidence (facility, scaling, availability): ENEA_POLIMI	GRS	JRC	LEI
1	A preliminary literature review revealed that the most relevant studies correspond to the validation efforts for the MASLWR [MDRP+14, MVWD12, WYS+19, WKL13, RGW+07], ESF [Ish16].	Pactel, BETHSY, SUPER MOBY DICK, MARVIKEN, LOFT, LOBI	OECD/NEA CCVM P1-2,14,21	Break flow of many SBLOCA tests (BETHSY, LOFT, LOBI, etc.)
2		Pactel, BETHSY, SUPER MOBY DICK	CCVM P1-2,9,26	General small scale tests; MASLWR
3		condensation: ThAI (e.g. ThAI 27) most experiments use steam to a certain degree	CCVM P1-9,26	General small scale tests; MASLWR
4	The experimental results correspond to MASLWR [MVWD12]	THAI / PANDA / MASLWR	CCVM P1-9,10,26	THAI, MASLWR
5	MASLWR experimental results are reported in [MVWD12]. Ref for Rayleigh-Benard cell phenomena	THAI	CCVM P1-5,6	THAI, MASLWR
6	No specific experimental facility for SMR. Ref for non-nuclear applications? MASLWR?	LIFE	CCVM P1-3,5,6	NRC SBLB
7		LIFE	CCVM P1-3,4,5,6	ULPU, NRC SBLB, THS-15 (VVER-1000 IVMR project)
8	Niu et al. Experimentally studied the mixing and stratification in SMR containments (MASLWR). The simulation results were also used to compare and verified with the experimental results [NZC+16]. Jiang et al. Used RELAP5 for nodalisation of upper half of containment [JPC19].	e.g. Thai HM 5 (different injection locations / init. Conditions)	CCVM P1-1,6,9,15,26	THAI
9			CCVM P1-5,6	THAI/MASLWR
10	Qi and Corradi's [WC16] is a very detailed experimental (MASLWR) + numerical (MELCOR) work on condensation models. Flow Dynamics and Condensation of Film Flows in Small Modular Reactors [Lee15] is also relevant.	WAFT	CCVM P1-5,9,26	MASLWR
11	A scaled down, reduced pressure suppression pool was designed to study condensation and mixing phenomena using scaled test conditions obtained from RELAP5	THAI	CCVM P1-10	Could be applicable from SFP pools experiments
12	While not directly for submerged containment outer wall, Niu et al. Experimentally studied the mixing and stratification in SMR containments (MASLWR). Albaldawy et al. performed a numerical and experimental study of thermal stratification outside a small SMR containment vessel (single phase) [AWC18].		CCVM P1-5,6	Could be applicable from SFP pools experiments
13			CCVM P1-3,5,6	NRC SBLB, PANDA, NOKO
14			CCVM P1-1,6	
15		SFP experiments	CCVM P1-5,6	Could be applicable from SFP pools experiments
16	Experimental results presented by [GS96] can possibly be used.	SFP experiments	CCVM P1-10	Could be applicable from SFP pools experiments.
17	No specific experimental results were found		CCVM P1-6	Could be applicable from SFP pools experiments; MASLWR

Comment	Level of knowledge - Model basis and validation (general or code specific): ENEA_POLIMI	GRS	JRC	LEI
1	Most of the SPES3 models available in literature employed the RELAP5 code coupled with GOTHIC [FAC+11, FMMV12, ACF+12]. Some studies also use TRACE [ACF+12]. MASLWR studies use RELAP5 [Bow12],TRACE [MDRP+14], ASTEC [DGSBC15], etc.Most STH codes have models for both one phase and two phase flows and also for condensation and evaporation. Uncondensable effect should be also considered	should be implemented in all codes (CDR1DIN table in ATHLET)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
2		should be implemented in all codes (CDR1DIN table in ATHLET)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable. Uncertainties due to user effect and nodalization.
3		should be implemented in all codes (CDR1DIN table in ATHLET)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable. Uncertainties due to user effect and nodalization.
4	Butt et al. Used RELAP5-SCDAP for MASLWR and High pressure containment and external cooling pool is modeled using pipe component [BIAA16].	water lev. depends on plant design, condensation aspects well defined in codes (dependend on nodalisation to some degree)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
5	TRACE was used to perform the simulation of natural circulation and Primary / containment coupling [MVDWD12]	should be implemented in all codes, heat transfer and material properties play a major role in all experiments, RPV structures not visible in COCOSYS (energy transfered , no	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow	Models applicable
6	No specific modelling (in term of correlation) for SMR. Ref for non-nuclear applications or AP1000?	material in some codes), in COCOSYS the rest water mass per zone can be specified, AC2 no direkt RPV (Athlet) structur in COCOSYS (WIP)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 Wall Boiling Model	Models applicable
7		S&A code can model core degradation lower plenum processes, stratification possible Can all core material melt? No direct contact of ATHLET structure to COCOSYS	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Code-dependent correlations for hemispheric surface
8	CFD results were accurate. The results were compared to RELAP5 code and found that the phenomena cannot be accurately predicted by that code [NZC+16].	Codes were able to simulate experiments with stratified conditions in the past. Can required nodalisation have an impact on other aspects?	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Large uncertainties in condensation and mixing
9		ideas for fine pool nodalisations exists (e.g. wetwell Fukushima), limited validation of nodalisation	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer	Models applicable
10		rivulet model for COCOSYS in development (status unknow), drainage along walls implemented in COCOSYS,	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
11	Results from the experiments were compared with the TRACE code predictions which reveal deficiencies in the code to predict the pool thermal stratification as TRACE was not	nodalisation above water surface has major impact decreasing water level impact on gas velocity probaly not modelled (at leat in COCOSYS)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
12	CFD results were accurate. The results of MASLWR were compared to RELAP5 code and found that the phenomena cannot be accurately predicted by that code [NZC+16]. Lack of ad-hoc correlation?	nodalisation guidelines for pools relativly new problem, several models / approches need to be tested	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable. Significant user effect
13		all lump parameter codes should be able to simulate boiling water stratified conditions very new topic, fine pool nodalistion need topic	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 Wall Boiling Model	Models applicable
14		domain of CFD codes, new models in lump parameter codes	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Basic physics. User effect.
15		heat transfer from submerged structure parts and bottom implimented, radiative heat exchange???, problem inhomogenous heat distributin in	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Basic physics. Models to be checked depending on boundary conditions.
16	Modelling results presented by [GS96] can possibly be used.	new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
17		new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable. Significant user effect

Comment	Importance Ranking - impact on containment heat removal function and accident sequence, consequences if not managed: ENEA POLIMI	GRS	JRC	LEI
1	No comments	Smalle water volume limits the stored energy, faster transition to two phase flow	No comments	Large amount of steam, but short term.
2		defines energy transfer from RPV -> PCV, and mass transfer rate in case of PCV leakage		Main water inventory release during this phase.
3		defines energy transfer from RPV -> PCV, and mass transfer rate in case of PCV leakage		Release is relatively low.
4		While the water level, in particular wetted surface area of the RPV, is of particular intrest, this question is nearly completly dependend on the plant design.		Important for evaluating the pressure build-up inside the containment.
5		??? Entirly governed by other points		Some of residual heat is removed by this path.
6		No different to other energy transfer topics discussed before (geometry main difference)		Subcooled boiling is expected to be the main mechanism.
7		basic models possible, inhomogenous / local effect probably have a mayor effect e.g. local early failure, first molten pool formation, limits convectiv heat transfer		IVR issues - pool boiling with significant local heat flux.
8		requires design specifications to calculate, if possible, probably only during specific accident conditions would limit effective heat transfer		Important for pressure build-up. Important in late phase, when smaller area for condensation with water wall.
9		The main questions is whether this can be addressed without geometrical data. Can a justified model without gemetrical data be implemented?		Depends on water level in the containment.
10		should also be a self-correcting effect: wet surface limits heat flow => pressure increase => higher energy density in atmos. => higher condensatin => more condensate		Important in late phase - the only path to remove heat.
11		probably most important energy transfer from the pool and most important mass transfer from the pool		Water wall is considered as UHS.
12		small error should probaly be self-correcting, slightly elevated temperature yields higher energy transfer		Not very important in early phase. Water level in the pool is high, RHRS is operating in early phase.
13		unless building is more or less airtight evaporation at surface should limit water temperatur, if boiling conditions occure only for short time energy/m² rather low		No boiling is expected in early phase. Boiling in late phase depends on containment pressure. Heat transfer in late phase is important since it's the only way to remove heat.
14		defines energy transfer to walls bottom of pool and avarage surface temp => evaporation		Heat transfer is mainly limited by CHF, not the flow field.
15		defines enery transfer to walls bottom of pool and avarage surface temp => evaporation		Important for the energy ballance, but it depends what are the boundary conditions and possibility to cool the water wall.
16		water level depends on plant design and mass release from pool (evaporation)		Water wall is considered as UHS.
17		accurate onset unimportant, later onset => higher density difference		Important in early phase for pressure build-up

Table 10: Comment fields related to the PIRT for an SBO

SBO / Comment		Containment safety system / Component e. g. RRC, water pool	phase	Description of macroscopic behaviour	microscopic phenomena	Level of knowledge - physical phenomena: ENEA_POLIMI	GRS	JRC	LEI
1	applicable to both NUWARD - NUSCALE	Containment vessel (internal)	depressurisation phase	Water accumulation in containment water level	volume/wall condensation	The physical phenomenon related towater level are well understood.	heat transfer (especially through containment wall), convection process	Integral effect, break flow	Physics well understood
2		Containment vessel (internal)	all phases	heat transfer, contact area with RPV wall	free convection 1-phase vs. 2-phase flow	The phenomena of heat transfer and natural circulation one phase flow are well understood.	condensation, nucleat / film boiling, heat transfer trhough containment wall, water steam table	HT wall/fluid	Physics well understood
3		Containment vessel (internal)	late phase	heat transfer, contact area with RPV wall before melt relocation	free convection, 2 phase flow under boiling conditions		nucleate vs. film boiling, nukiyama curve, radiativ heat transfer, heat conduction (e.g. RPV wall), heat radiation, heat distribution / release from melt inside RPV	HT wall/fluid	Physics well understood
4		Containment vessel (internal)	late phase	heat transfer, contact area with RPV wall after melt relocation	free convection, 2 phase flow under boiling conditions		nucleate vs. film boiling, nukiyama curve, radiative heat transfer, focussing effect, crust formation, heat conduction	HT wall/fluid, CHF	Physics well understood, local effects are important.
5		Containment vessel (internal)	all phases	Atmospheric composition, stratification (e. g. NC, steam)	heat transfer, condensation, buoyancy	The phenomena is known	density distribution, formation of very inhomogenous heat transfer conditions, production of NC gases (oxidation)	Integral effect	Physics well understood in small scale, but integral facility with specific geometry is important
6		Containment vessel (inner wall)	all phases	heat transfer, water contact area with cont. wall	water level, free convection	The microscopic phenoma are well understood but there is no specific study for SBO	density differences, nucleate / film boiling, convections loops in pool (energy transfer on other structures / to atmosphere)	HT wall/fluid	Physics well understood
7		Containment vessel (inner wall)	all phases	heat transfer, atmoshere contact area with cont. wall	wall area, condensation, rivulets, wetted area	The microscopic phenomena of condensation of flows are well studied in literature. But no specific study for the particular case was found.	atmospheric composition above water surface (different heat capacities), inhomogenous heat distribution in wall structures, wall roughness	HT wall/steam atmosphere, condensation	Physics well understood. Scaling and film flow issues on high vertical wall.
8		Submerged containment water pool (outer surface)	all phases	Heat transfer at water surface (evaporation)	Thermal stratification	The phenomena is known	gas velocity, denisty differences, humidity, temperatur, formation of convection loops over water surface	Evaporation	Physics well understood
9		Submerged containment outer wall	early phase	Heat transfer along cont. wall, natural convection (single phase)	Thermal stratification (water level)	The phenomena is known	density differences, reynolds / nusselt number	HT wall/fluid	Physics well understood
10		Submerged containment outer wall	early/late phase	Heat transfer along wall, natural convection (boiling conditions)	Thermal stratification (water level)		nucleate vs. film boiling, nukiyama curve, densitiy inhomogeneity nusselt / reynolds number, unless heat flow is very high or water level very low, evaporation should domintae	HT wall/fluid	Physics well understood
11		Submerged containment water pool	all phases	flow field in water pool	3D- effects symmetric vs. non-symmetric	The phenomena are not well known (strongly dependent on geometry)	density diffrences, heat transfer structure -> water local effect: nucleate / film boling	flow field, integral effect	Specific geometry is important
12		Submerged containment water pool	all phases	heat transfer to outer building	stratification		evaporation at pool surface, convection to pool structures, heat conduction in structures, radiation	HT wall/fluid	Specific geometry is important
13		Submerged containment water pool	all phases	heat transfer to outer building structure	stratification		see point 12	HT wall/fluid	Specific geometry is important
14		Submerged containment water pool (NuScale, NUWARD?)	late phase	water level in water pool	evaporation	The phenomena of heat and mass transfer is well understood.	gas velocity at pool surface, gas humidity convection in building	Evaporation	Physics well understood
15	NUWARD	Submerged containment NUWARD water pool	early phase	Onset of natural convection	initial & boundary conditions, mass flow		density differences, reynolds / nusselt number water property tables	Natural convection	Physics well understood
16		Piping RRC to water wall, NUWARD	all phases	Flow dynamics single vs. two-phase	turbulent phase-interface friction approaches from heat transfer handbooks		reynolds / nusselt number, density differences, heat transfer, water / steam property, NC in late phase	Natural convection	Single phase is well understood. For two-phase - local effects are important.
17		Piping RRC to water wall NUWARD	all phases	Pressure loss	frictional drag + local resistences	The microscopic phenoma are well understood and the RELAP7 Theory manual describes in details the different available models for the frictional drag and local resistances.	reynolds / nusselt number, density differences, heat transfer, water / steam property, NC in late phase with focus on plant data	turbulent flow	Single phase is well understood. For two-phase - local effects are important.
18		RRC NUWARD	all phases	perfomance under different boundary conditions	one phase / two phase flow	One phase and two phase flows are well understood but no specific study for NUWARD RRC was found.	see point 16/17		The key modifier is two-phase flow. The range of different flow regimes could affect the performance significantly.
19		RRC NUWARD	all phases	Onset of natural convection	buyoancy initial & boundary conditions, density differences, stratification		atmospheric composition (NC!), nusselt / reynolds number quetion is too unspecific		Single phase is well understood. For two-phase - local effects are important: onset of boiling.
20		RRC NUWARD	all phases	influnce of type of heat exchanger / condenser	flow phenomena	The microscopic phenoma are well understood and the RELAP7 Theory manual describes in details the different available models for the frictional drag and local resistances.	density differences, water steam data, reynolds / nusselt number		The range of different boundary conditions is important
21	NUSCALE	Submerged containment NuScale water pool	early phase	Onset of natural convection	initial & boundary conditions, density differences, stratification	The microscopic phenoma are well understood and the models described in point 15 are relevant to this case too. However, a model specifically for NuScale design was not found.	density differences, reynolds / nusselt number		Physics well understood. Specific geometry is important.
22		external SACO NuScale	all phases	flow phenomena	one phase vs. two phase flow	While the phenomena are well understood, no specific study related to SACO were found in open literature	nusselt / reynolds number, densitiy differences, nucleate / film boiling		Single phase is well understood. For two-phase - local effects are important: onset of boiling.
23		external SACO NuScale	all phases	flow phenomena	internal flow,one phase vs. two phase flow boundary cond.		impact of NC, nusselt / reynolds number, densitiy differences, nucleate / film boiling		Internal flow in the condenser from SG side? Two phase local effects could be important.
24		external SACO NuScale	late phase	partly flooded pool perfomance of SACO under different wetting conditions	wetting, heat transfer		nukiyama curve, nusselt / reynolds number, pool stratification NC could prevent reflux operation very dependent on design details		Complex boundary conditions - steam/water/air
25		RRP cooling circuit	early phase	Onset of natural convection (NuScale)	buoyancy initial & boundary conditions, density differences, stratification		density differences, reynolds / nusselt number, gemetrical details		Single phase is well understood. For two-phase - local effects are important: onset of boiling.

Comment	Level of knowledge - Experimental evidence (facility, scaling, availability): ENEA_POLIMI	GRS	JRC	LEI
1	The experimental results correspond to MASLWR [MVWD12]	MASLWR	CCVM P1-2,14,21	THAI, MASLWR
2	Chunxian performed experimental investigations on the characteristics of the passive safety systems under LOCA and SBO. In addition the experimental data were used to assess CATHARE simulating the cold leg LOCA test. However, the experiment was only for primary circuit.	THAI / MASLWR	CCVM P1-5,6	THAI, MASLWR
3		LIFE	CCVM P1-3,5,6	NRC SBLB
4		LIFE	CCVM P1-3,4,5,6	ULPU, NRC SBLB, THS-15 (VVER-1000 IVMR project)
5	Niu et al. Experimentally studied the mixing and stratification in SMR containments (MASLWR). The simulation results were also used to compare and verified with the experimental results [NZC+16]. Jiang et al. Used RELAP5 for nodalisation of upper half of containment [JPC19].	e.g. Thai HM 5 (different injection locations / init. Conditions)	CCVM P1-1,6,9,15,26	THAI
6	No experimental studies for SBO for containment were found in literature.	MASLWR	CCVM P1-5,6	THAI/MASLWR
7		SFP Experiments, WAFT	CCVM P1-5,9,26	MASLWR
8	A scaled down, reduced pressure suppression pool was designed to study condensation and mixing phenomena using scaled test conditions obtained from RELAP5 code results of a loss of coolant accident in a simplified boiling water reactor [NPR+06].	SFP Experiments, THAI	CCVM P1-10	Could be applicable from SFP pools experiments
9	No study simulating SBO for containment outer wall was found. While not directly for submerged containment outer wall, Niu et al. Experimentally studied the mixing and stratification in SMR containments (MASLWR). The simulation results were also used to compare and verified with the experimental results [NZC+16]. Albaldawy et al. performed a numerical and experimental study of thermal stratification outside a small SMR containment vessel [AWC18].		CCVM P1-5,6	Could be applicable from SFP pools experiments
10			CCVM P1-3,5,6	NRC SBLB, PANDA, NOKO
11			CCVM P1-1,6	
12			CCVM P1-5,6	
13			CCVM P1-5,6	
14	No experimental studies for SBO for containment were found in literature. Experimental results presented by [GS96] can possibly be used.		CCVM P1-10	Could be applicable from SFP pools experiments
15			CCVM P1-6	Could be applicable from SFP pools experiments; MASLWR
16			CCVM P1-6	
17				
18				
19				
20	The specific model has not been studied.	PANDA, PASI		
21		MASLWR		Could be applicable from SFP pools experiments
22		PASI / PANDA / INKA		
23		PASI / PANDA /INKA		
24		PASI / PANDA / INKA		
25				

Comment	Level of knowledge - Model basis and validation (general or code specific): ENEA_POLIMI	GRS	JRC	LEI
1	Riley provided a proof of concept for the use of RAVEN and RELAP5-3D for Risk Informed Safety Margin Characterization [Ril14] and focussed on MASLWR.	water lev. depends on plant design, condensation aspects well defined in codes (dependend on nodalisation to some degree)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
2	Santinello and Ricotti performed numerical investigation of the long-term decay heat removal strategy in IRIS-160 with Relap5-Mod3.3. A sliced model was used: the total volume of containment was subdivided into two parallel pipes, upward vertically oriented, made of 56 elementary volumes connected by transversal crossflow junctions. The sensitivity analysis identified the nodalization of the reactor containment as a modeling and numerical issue.	should be implemented in all codes, heat transfer and material properties play a major role in all experiments, RPV structures not visible in COCOSYS (energy transfered , no radiation)	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow	Models applicable
3		surface area, inclination (maybe material in some codes), in COCOSYS the rest water mass per zone can be specified, AC2 no direkt RPV (Athlet) structur in COCOSYS (WIP)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 Wall Boiling Model	Models applicable
4		S&A code can model core degradation lower plenum processes, stratification possible Can all core material melt? No direct contact of ATHLET structure to COCOSYS	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Code-dependent correlations for hemispheric surface
5	CFD results were accurate. The results were compared to RELAP5 code and found that the phenomena cannot be accurately predicted by that code [NZC+16].	Codes were able to simulate experiments with stratified conditions in the past. Can required nodalisation have an impact on other aspects?	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Large uncertainties in condensation and mixing
6	Considerations for severe accident management under extended station blackout conditions in nuclear power plants by Park et al. considers SBO but only for PWR and uses MAAP4 code [PS16].	Segmented structures (water / gas) are implemented in COCOSYS, heat transfer is part of any theromhydraulic experiment	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer	Models applicable
7		part of all thermohydraulic analsis perfromed	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
8	Results from the experiments were compared with the TRACE code predictions which reveal deficiencies in the code to predict the pool thermal stratification as TRACE was not initially developed for predicting such phenomena [NPR+06].	nodalisation above water surface has major impact decreasing water level impact on gas velocity probaly not in all codes modelled	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
9	CFD results were accurate. The results were compared to RELAP5 code and found that the phenomena cannot be accurately predicted by that code [NZC+16].	nodalisation guidelines for pools relativly new problem, several models / approches need to be tested	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable. Significant user effect
10		all lump parameter codes should be able to simulate boiling water stratified conditions very new topic, fine pool nodalistion need topic	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 Wall Boiling Model	Models applicable
11		domain of CFD codes, new models in lump parameter codes	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Basic physics. User effect.
12	No study simulating SBO for containment	fine pool nodalisation is new topic, very design dependent, nodailsation has big impact on evaporation	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Basic physics. Models to be checked depending on boundary conditions.
13		see point 12	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Basic physics. Models to be checked depending on boundary conditions.
14	Modelling results presented by [GS96] can possibly be used.	water level in one pool zone easy to simulate, inhomogenous pool conditions are new topic (see previous points)	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 5.13.4 The Thermal Phase Change Model	Models applicable
15		new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Models applicable. Significant user effect
16		reflux condensor simulation should be governd by all codes	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Models to be checked
17		see point 15, general model okay, but plant data could be a problem	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Models applicable
18		see point 16/17	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow	Models to be checked
19		Can not be answered without details elevated energy release in pool limits pool mixing => stratification very important	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow	Models applicable. Large uncertainties. Significant user effect
20	The specific model has not been studied.	new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Models to be checked
21	Susyadi et al. Performed an analysis on inadvertent operation of decay heat removal system in NuScale reactor. The simulation covers heat transfer transient in the primary loop, secondary system, DHRS and reactor pool [SETT19]. Skolik et al. Performed an Assessment of RELAP/SCDAPSIM for turbine trip transient in NuScale-SMR [STPFA18]. Neither of these are studies for the case in point but they reveal how the component has been modelled in literature.	new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Models applicable
22		energy transfer distribution water / gas from ATHLET <> COCOSYS currently not possible with decreasing water lvl.	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Models to be checked
23		reflux condensor operation is well defined in S&A codes	ANSYS CFX Solver Theory Guide, R18.2, 1.5 Multicomponent flow, 5.13.4 The Thermal Phase Change Model	Models to be checked
24		see above points	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Models to be checked
25		new problem, very limited experience / guidelines for fine pool nodalisation only experience is based on Fukushima Ww	ANSYS CFX Solver Theory Guide, R18.2, 1.9.5.2 Heat Trasfer, 1.3 Buoyancy	Models applicable. Large uncertainties. Significant user effect

Comment	Importance Ranking - Impact on containment heat removal function and accident sequence, consequences if not managed: ENEA POLIMI	GRS	JRC	LEI
1	No comments	While the water level, in particular wetted surface area of the RPV, is of particular intrest, this question is nearly completly dependend on the plant design	No comments	Important for evaluating the pressure build-up inside the containment.
2		No different to other energy transfer topics discussed before (geometry main difference)		Important in late phase, when RRC is not active anymore.
3		No different to other energy transfer topics discussed before (geometry main difference)		Subcooled boiling is expected to be the main mechanism.
4		basic models possible, inhomogenous / local effect probably have a mayor effect e.g. local early failure, first molten pool formation, limits convectiv heat transfer		IVR issues - pool boiling with significant local heat flux.
5		requires design specifications to calculate, if possible, probably only during specific accident conditions would limit effective heat transfer area,		Important for pressure build-up. Important in late phase, when smaller area for condensation with water wall.
6		very small contribution to energy transfer from containment		Depends on water level in the containment.
7		only important in late phase with low decay heat, unless water lvl. drops very fast (e.g. leak in pool)		Important in late phase - the only path to remove heat.
8		heat transfer probably mostly due to evaporation, mayor impact on water lvl.		Water wall is considered as UHS.
9		small error should probaly be self-correcting, slightly elevated temperature yields higher energy transfer		Not important in early phase. All residual heat is removed by RRP.
10		unless building is more or less airtight evaporation at surface should limit water temperatur, if boiling conditions occure only for short time energy/m² rather low		No boiling is expected in early phase. Boiling in late phase depends on containment pressure. Heat transfer in late phase is important since it's the only way to remove heat.
11		defines energy transfer to walls bottom of pool and avarage surface temp => evaporation		Heat transfer is mainly limited by CHF, not the flow field.
12		heat transfer from pool defines water lvl. Develoment		Important for the energy ballance, but it depends what are the boundary conditions and possibility to cool the water wall.
13		see point 12		Important for the energy ballance, but it depends what are the boundary conditions and possibility to cool the water wall.
14		water level depends on plant design and mass release from pool (evaporation)		Water wall is considered as UHS.
15		knowledge of precise onset of cenvection should have no impact on general safety concerns (thermohydraulic)		Not important in early phase. All residual heat is removed by RRP. As long as there's water in the pool, RRP is sufficient.
16		unless geometry is really of, user experience from PWR steam generator operation under accident conditions should be sufficent to govern this point heat transfer is very important		This is the main residual heat removal safety system for early accident phase.
17		design data could be problematic		This is the main residual heat removal safety system for early accident phase.
18		see point 16/17		This is the main residual heat removal safety system for early accident phase.
19		stratified pool, limited energy transfer from pool to structure, higher evaporation rate		Circulation is very important, but in case of boiling in the heat exchanger, the density difference more than sufficient.
20		Precise simulation of onset unimportant for thermohyraulic results		This is the main residual heat removal safety system for early accident phase.
21		knowledge of precise onset of cenvection should have no impact on general safety concerns (thermohydraulic)		Important for SACO performance, but SACO are considered capable to remove heat until dry-out.
22		stratified pool, limited energy transfer from pool to structure, higher evaporation rate		This is the main residual heat removal safety system for early accident phase.
23		unless geometry is really of, user experience from PWR steam generator operation under accident conditions should be sufficent to govern this point heat transfer is very important		This is the main residual heat removal safety system for early accident phase.
24		ultimate heat sink, only part of the pool available due to elevated heat exchanger position		This is the main residual heat removal safety system for early accident phase.
25		Precise simulation of onset unimportant for thermohyraulic results		Circulation is very important, but in case of boiling in the heat exchanger, the density difference more than sufficient.

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