SASPAM-SA: Assessment of the relevance and applicability of existing experimental databases to iPWR

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ABSTRACT

One of the objectives of SASPAM-SA, in particular Work Package 3 (Applicability and Transfer of the Existing SA experimental database for iPWR Assessment), is to evaluate the relevance and applicability of the existing experimental database to iPWR. Based on postulated plant severe accident scenarios, identified and investigated in the project, the main boundary conditions and the specific features of iPWR are

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determined and compared to those of large LWR. Based on this comparison, the applicability of the existing experimental data to iPWR is assessed for in-vessel, containment, source term and ex-vessel coolability (if applicable) phenomena. The specific data to be evaluated include, e.g., natural circulation, debris bed formation, liquid melt spreading, steam explosion, re-flooding of an overheated core, in-vessel melt pool formation, corium cooling under water, hydrogen distribution, combustion and mitigation, aerosol characteristics, transport and hygroscopic growth, iodine speciation and mitigation, as well as pool scrubbing. If needed, methods will be developed to extend the applicability of existing data. Finally, the potential need for new experiments is determined. In this paper, a summary of the work done during the first project year is given.

KEYWORDS
iPWR, experimental data, SASPAM-SA

1. INTRODUCTION

Small Modular Reactors (SMR) are one of the key options for the near-term deployment of new nuclear reactors. Currently in Europe there is a growing interest towards the deployment of SMRs, and several activities are underway in many countries preparing for possible licensing needs. To address this need, an Horizon Euratom collaboration project SASPAM-SA (Safety Analysis of SMR with PAssive Mitigation strategies - Severe Accident), coordinated by ENEA (Italy), was started in October, 2022, for four years. The key objective of SASPAM-SA is to investigate the applicability and transfer of the operating large Light Water Reactor (LWR) knowledge and know-how to the near-term deployment of integral PWR (iPWR), in the view of the European licensing analyses needs with emphasis on severe accidents and emergency planning zone [1].

Advanced designs, such as iPWRs, are in general characterized by common features with the current operating large-LWR and by other specific features typical of their inherent evolutionary designs, providing safety advantages that reinforce the first three levels of the Defence-in-Depth (DiD) principle. However, even if a plant is designed with advanced inherent features (through the reinforcement of the 1,2,3 DiD levels) allowing a reduction of the Core Damage Frequency (CDF), independent features for preventing and mitigating a severe accident sequence have to be included in its design (DiD level 4) together with the offsite emergency response (DiD level 5). Therefore, some scenarios that could lead to severe accidents need to be postulated and deterministically studied [2]. Though most of the significant severe accident phenomena have been the subject of research efforts in the past, those efforts have focused on large-LWRs. Due to different geometries and configuration (e.g. integral RPV, larger core surface-to-volume and coolant inventory-to-power ratios within RPV), specific phenomena (e.g. closed coupling of the reactor pressure vessel and the containment in accident conditions, low pressure phenomena), the use of specific components (e.g. compact steam generator, passive safety systems), and different operating parameters of iPWRs and large-LWRs (e.g. lower core power), the accident progression can be expected to be different in iPWRs as compared to large LWRs. As a consequence, the conditions in the RPV and in the containment of an iPWR can differ from those in large-LWRs [1,2,3,4]. Thereby, the applicability of the available data developed for large LWRs also to iPWR technology has to be proven.

The main objectives of the Work Package 3 of the SASPAM-SA project: “Applicability and Transfer of the Existing severe accident experimental database for iPWR Assessment” are i) to study the relevance and applicability of the existing experimental database to iPWR, ii) to develop methods to extend the applicability of existing data, and iii) to identify the need for new experiments. The relevant phenomena will be identified, and the review of the current experimental database will be done considering the following phenomena: a) In-vessel degradation and coolability; b) Containment, including hydrogen ignition and selfsustained combustion; c) ST; d) Ex-vessel coolability, if any ex-vessel phenomenology will be identified in the project. It is worth noting that SASPAM-SA/WP3 will be tightly linked to EU SEAKNOT, supporting the inclusion of specific water-cooled-SMR phenomena in a mid-term severe accident research roadmap.

2. METHODS

2.1. iPWR designs

The applicability of the large LWR data to iPWRs will be assessed for two generic iPWR designs, Figure 1. The two designs are characterized by different evolutionary innovations in comparison to larger operating reactors. Even though the designs are generic, they have common features with iPWR designs which are under development, and thereby available data in the open literature can be used in the work. The two generic designs are:

- Design 1: iPWR characterized by a submerged containment and an electric power of about 60 MWe;
- Design 2: iPWR characterized by the use of several passive systems, a dry containment and an electric power of about 300 MWe.

These two generic reactor concepts include the main iPWR design features considered in some of the promising designs ready to go on the European market allowing a broad assessment of the capability of severe accident and CFD codes to simulate the severe accident phenomena typical of iPWRs.

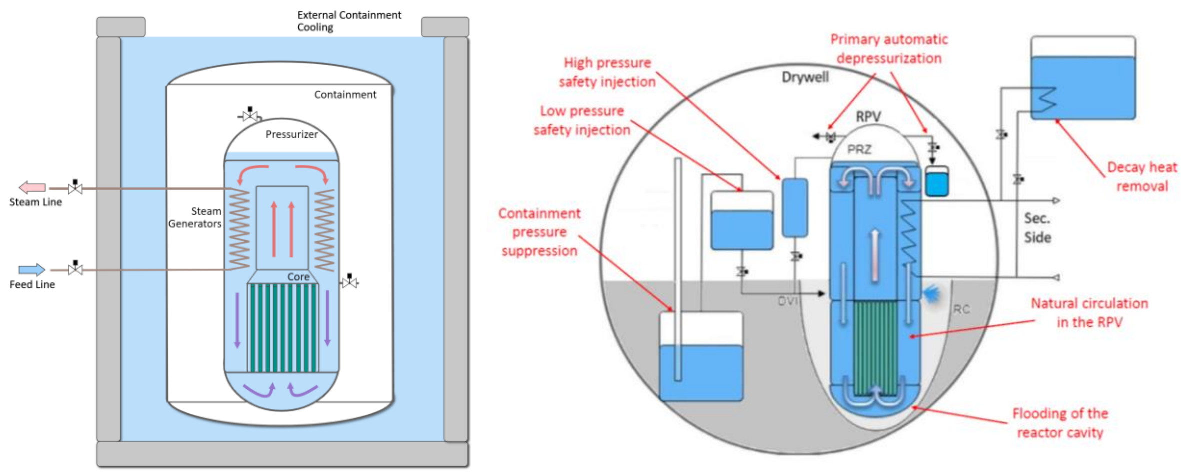

Figure 1. The designs 1 (on the left) and 2 (on the right) used in the SASPAM-SA project.

2.2. Assessment of the Data

The outline of the methodology to be applied to evaluate the applicability of the existing experimental data to iPWRs is depicted in Figure 2. A review of the existing experimental database, relevant to severe accidents, will be done for the following severe accident phenomena:

a) In-vessel degradation and coolability;
b) Containment, including hydrogen risk;
c) Source term; and
d) Ex-vessel coolability, if any, based on the accident analyses of iPWR design 1 and design 2.

Based on the postulated plant severe accident scenarios as identified and investigated for designs 1 and 2, the main boundary conditions and the specific phenomenological features will be determined. The predominant phenomena, i.e., those phenomena having a decisive impact on the accident progression, will be identified, and governing equations determined. The phenomena will be described by the most significant parameters and / or dimensionless numbers. Based on the main phenomena, potential facilities in which these phenomena have been investigated will be explored, and suitable tests in those facilities selected for further assessment. In the next step, the key features of the selected facilities and tests will be listed, including the facility scaling factor and other relevant geometrical and operational features. Comparison with iPWR severe accident conditions for SASPAM-SA designs 1 and 2 can be done, for example, using a table in which all the main parameters and, when deemed useful, dimensionless numbers are presented.

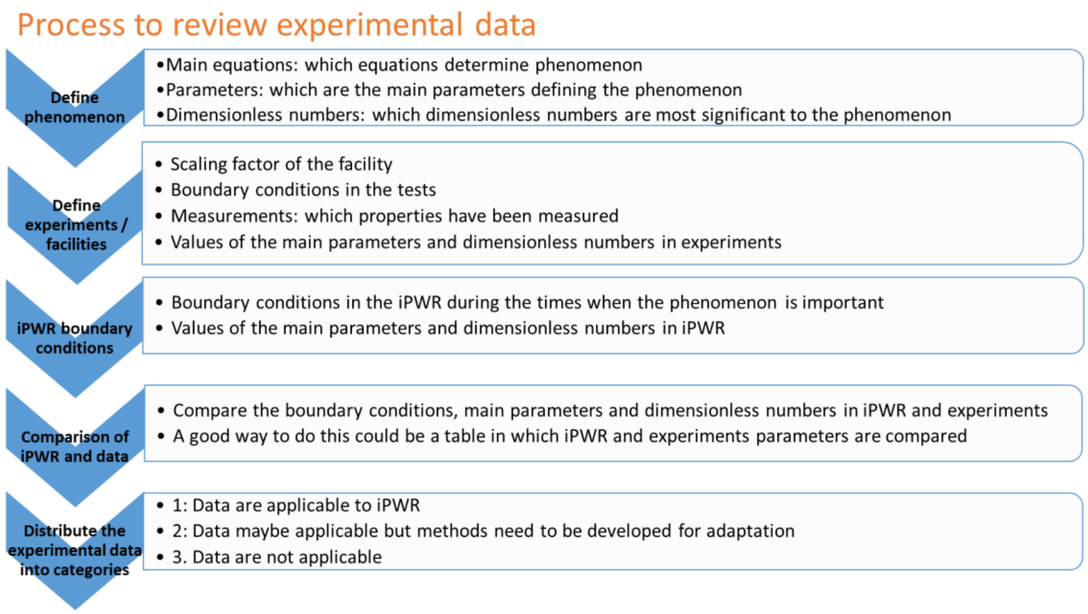

Figure 2. The proposed methodology for evaluation of the applicability of existing experimental data to iPWRs.

Based on the comparison of the experimental data with the iPWR designs, assessment of the applicability of the data to iPWRs will be made. The data will be divided into three categories:

i) data which are directly applicable to iPWR,
ii) data which can be used by developing extrapolation and other methods to extend their applicability to iPWR conditions, and
iii) data which are not applicable to iPWRs.

If the facility scaling is appropriate and the main parameters and dimensionless numbers during iPWR severe accidents fall within the range of parameters in the experiments, the data can be assessed as belonging to category i), applicable to iPWRs. For the category ii), application methods will be proposed and developed in further work.

In the end of the investigation, to be reported later, the phenomena to which no applicable data are available or to which the database is not sufficient will be identified, and the critical experimental data needs to enable credible SA analysis of iPWRs will be determined.

2.3. Investigated Phenomena

To optimize the use of resources, the phenomena to be investigated were distributed between different scientists. The following phenomena are included:

a) Natural circulation: ENEA;
b) In-vessel degradation and coolability by KTH, RATEN, SSTC NRS, and TUS,
c) Containment: CIEMAT, CNRS-ICARE, FZJ, KTH, PSI and IRSN,
d) Source term: VTT, PSI, CIEMAT and IRSN,
e) Ex-vessel coolability: If ex-vessel phenomena are observed in the severe accident scenarios postulated for iPWR designs 1 and 2, these phenomena will be studied by KTH, TUS, RATEN and SSTC NRS.

3. FIRST RESULTS

3.1. Natural Circulation

The passive systems relying on natural circulation are, on one side, advanced solution to increase the inherent safety of the plant (e.g. there is no need of pump), on the other hand a) they required more investigation for assessing the functional failure related to the thermal-hydraulic phenomena driving the operation of the systems and assess the related uncertainties, b) may still need an active initiation, and c) are characterized by less operational experience [5,6]. Considering this, the impact of passive systems operation on postulated severe accident progression needs to be assessed.

iPWR designs rely on natural circulation during accident situations and for some designs also in steady operational condition [e.g.,3]. To assess if the existing experimental data for natural circulation are applicable to iPWRs, ENEA has selected a number of facilities in which experiments for natural circulation have been conducted. The majority of the experiments have been carried out at Design Basis Accident (DBA) conditions but some may be applicable to characterize natural circulation in severe accident conditions. When selecting the data to be assessed, the focus was on thermal-hydraulics of integral RPV, primary/containment coupling, and on passive systems that affect the progression of severe accident scenarios[1]. Both the scaling factors and other features of the potential facilities were listed, and based on those, a series of tests in each facility was selected for further review.

For natural circulation, the main affecting parameters are the geometry, e.g., elevation between the source and sink, and piping diameters; phases: single-phase/two-phase; pressure and temperature fields; pressure losses, both local and continuous; heat provided/removed in the core and heat exchangers; as well as possible presence of non-condensable gases. As non-dimensional numbers, e.g. Richardson and SG heat transport number, are important numbers to be considered. These are the parameters which are compared in the experiments with those of iPWR in DBA and severe accident conditions as computed in the WP2 of the SASPAM-SA project.

The work started with assessment of data from the OSU-MASLWR facility [4]. For natural circulation in the RPV, three relevant tests were identified: DOE OSU-MASLWR-002, DOE OSU-MASLWR-003A, and IAEA ICSP SP-2. Figure 3 shows an example comparison of the Richarson number range [7] for the test OSU-MASLWR-002 and the design 2 DBA data. It is seen that the experimental Richarson number envelop some of the design 2 calculated data. Based on the SASPAM-SA schedule, currently DBA and severe

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accident calculated data are under collection and the comparison will be carried out based on the results of all the severe accident codes used in SASPAM-SA (AC2, ASTEC, MAAP, MELCOR).

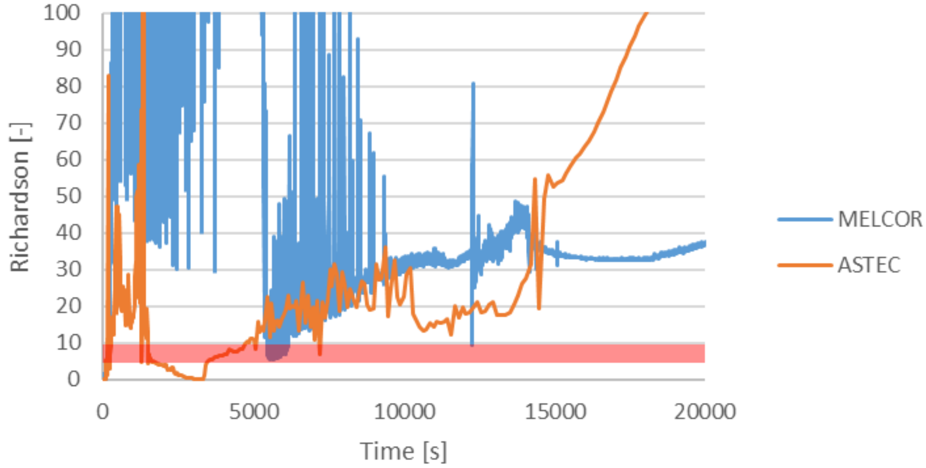

Figure 3. Comparison of the OSU-MASLWR-002 Richardson number range against design 2 data in DBA condition.

3.2. In-Vessel Cooling and Degradation

3.2.1. Re-flooding of rod-like geometry

When an over-heated core is re-flooded, steam will oxidize the Zr in the cladding leading to hydrogen generation and eventually to cladding failure. The QUENCH program carried out at the KIT has investigated phenomena related to reflooding since mid 1990s [8]. For the assessment in this work, QUENCH-06 test (OECD ISP-45) was chosen [9]. The QUENCH facility and SASPAM-SA designs 1 and 2 have been compared, and the main phenomena relevant to reflooding defined. In continuation, scenario analysis data will be used to compare with QUENCH-06 data. Potentially, other QUENCH tests can be added in the analysis.

3.2.2. Melt jet behaviour and steam explosion

The following melt jet and in-vessel phenomena will be assessed based on experimental data available at Royal Institute of Technology in Stockholm (KTH): Melt jet breakup and debris bed formation (DEFOR-A and DEFOR-S tests), liquid melt spreading under water (PULiMS-E and SES-E tests), lower head failure and breach ablation / plugging during melt release, particulate debris spreading (PDS-C tests), steam explosion in stratified melt-coolant configuration, and melt propagation in a porous debris bed. In addition, lower head failure test data are available from DEFOR-MGF experiments.

3.2.3. In-vessel cooling of a molten core

To assess in-vessel coolability and degradation, the following parameters need to be investigated:

- Reduced core power, less power-to-surface ratio;
- Materials (vessel, vessel internals, core);
- Geometry (incl. vessel internals);
- Containment atmosphere composition.

Data for lower plenum phenomena related to in-vessel cooling of a molten core are available from the test series LIVE (Large-scale Tests on In-vessel Melt Relocation and Retention) conducted in the Karlsruhe Institute of Technology [10]. The LIVE-L1 test was focused on the core melt behavior in the lower plenum of the RPV and the influence of the cooling of the vessel outer surface with water [11,12]. The LIVE3D test facility simulates the lower plenum of a water-cooled reactor pressure vessel and investigates the transient and steady state thermal-hydraulics and heat transfer of solid and liquid corium under various accident scenarios. Experimental data from five tests are assessed in this work, i.e., LIVE-1, -2, -L3A, L4 and L5L. The main data relevant to iPWRs are shown in Table 1. According to preliminary assessment, comparison should use Pr, Ra and Nu numbers.

Table 1. The main parameters of the LIVE experiments to be compared with iPWR conditions.

Melt characteristic	LIVE-1	LIVE-2	LIVE-L3A	LIVE-L4	LIVE-L5L
Height [m / %]	0.31 / 62.4	0.31 / 62.4	0.31 / 62.4	0.435 / 87.6	0.435 / 87.6
Volume [l / %]	120 / 46.8	120 / 46.8	120 / 46.8	210 / 81.9	210 / 81.9
LH heat flux min/max [W/m^2]	1.5E+03/ 1.0E+04	1.25E+03/ 8.0E+03	1.5E+03/ 1.73E+04	4.91E+02/ 1.94E+04	7.09E+2/ 2.26E+4
$Q_{heating}$ [W]	-	-	-	18064.2	18088
Q_{wall} [W]	-	-	-	14488.7	14661
Q_{wall}/ $Q_{heating}$	-	-	-	0.802	0.81
Average heat density [W/m^3]	-	-	-	87692	87970
ν [m^2/s]	-	-	-	1.56E-06	1.56E-06
Pr	-	-	-	9.3	9.3
Nu	-	-	-	-	227
Ra	-	-	-	4.31E+13	4.29E+13

3.3. Containment

3.3.1. Hydrogen distribution

The hydrogen risk may be reduced in iPWR as compared to large PWRs due to inerted or sub-atmospheric containments. However, as the containment and reactor vessel are closely coupled during accidents, the effect of hydrogen is not only the risk of explosion but also its effect on the establishment and continuity of natural circulation needed to cool the core during accidents.

Experimental data for the hydrogen distribution as well as natural circulation are available from various test programs in the PANDA facility at PSI [13]. The available data will be reviewed and evaluated using the methodology presented in section 2.

3.3.2. Hydrogen combustion

As air ingress can not be completely excluded in iPWR containments [14], hydrogen combustion data from a series of tests conducted at CNRS are assessed. Among the tests to be investigated are those in the experimental programs ANR-PIA-MITHYGENE, ANR-PHYSSA and CNRS Projects on H_2 based mixtures (different diluents).

iPWR containments are typically smaller than those in large LWRs with restricted geometries which tend to cause flame acceleration in case hydrogen combustion occurs. In addition, hydrogen release may be rather rapid having also an impact on combustion behaviour. The expected hydrogen combustion conditions in iPWR (SMR) as compared to large PWRs are depicted in Figure 4 showing that data might be missing at conditions relevant to iPWRs. Further work will be conducted to evaluate the conditions in the iPWRs and experimental data, and if deemed needed, selected tests may be carried out to fill the gaps of missing data.

For SMRs, the path towards flammable mixtures is through rich mixtures, unlike for LWR for which it is through the lean branch, Fig. 2. The knowledge on the explosion risk for the relevant mixtures is rather scarce and it will be the goal of this project to derive methods to enhance the knowledge for these mixtures. Moreover, the effect of the initial pressure and temperature on the flammability limits and minimum ignition energy will be derived. Finally, the presence of other gases and/or particles can have an important effect of the flammability/severity domain.

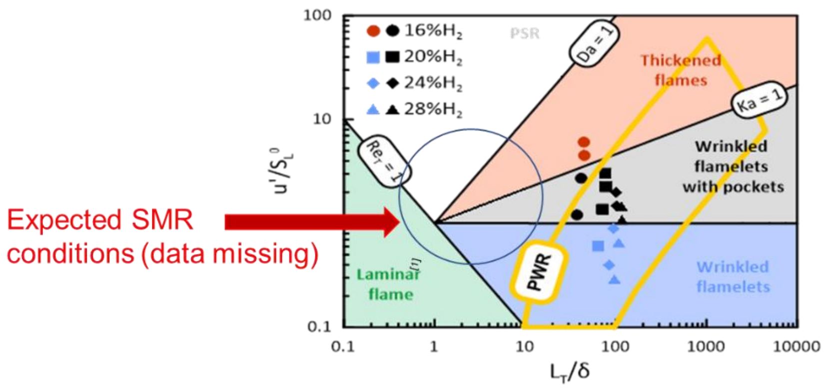

Figure 4. Hydrogen combustion regimes with an indication of the area of iPWR conditions.

3.3.3. Hydrogen mitigation with passive auto-catalytic recombiners (PARs)

PARs are installed in non-inerted LWR containments to reduce the hydrogen concentration in the containment atmosphere. Their performance at different containment conditions has been studied in series of test campaigns, e.g., France: H2PAR, KALI (1995 – 1999); Germany: HGF-NUSAFE (on-going), REKO-I to REKO-III (2005 – 2018), THAI (on-going); Canada: various AECL/CNL programs; European projects: SAMHYCO-NET (2017-2022) and AMHYCO (2020 on-going); and OECD/NEA projects: THAI/THEMIS HR series (2007 on-going). Based on these investigations, the PAR response to different pressures, gas mixtures, humidity, temperature and the presence of inhibitors has been broadly assessed [15].

While PAR operation in the SMR designs under consideration could only be conceivable for air-ingress scenarios, the accident conditions in iPWR containments would be distinctly different from large LWRs. Depending on the time of the air ingress, accident scenarios would follow pathways starting from inert conditions instead of air, Figure 5 [15]. Based on the existing accident analyses, there is lack of data for PAR performance at pressures higher than 0.5 MPa, start-up at extremely wet conditions, as well as fast H2 injection rates. Furthermore, there is the need to identify for both designs, if and where the installation of PARs could be feasible and meaningful. In addition to the containment, these considerations should also include reactor and auxiliary buildings.

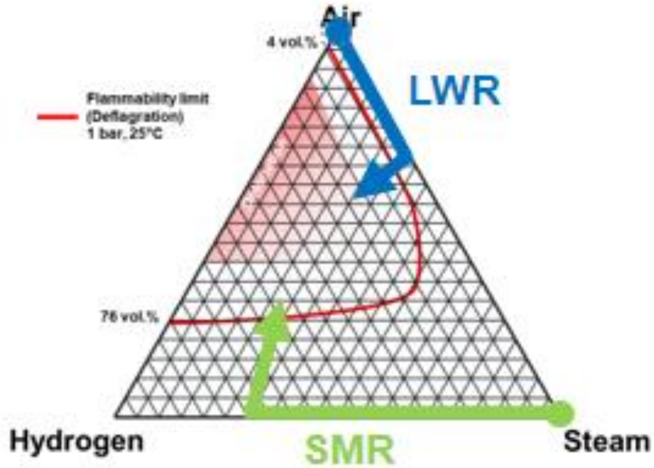

Figure 5. Shapiro diagram for hydrogen flammability indicating the pathways in large PWRs and iPWRs.

3.4. Source Term

3.4.1. Aerosol characteristics

The characteristics of aerosol particles formed during severe accidents would depend, among other things, on the type and stage of the accident, the conditions (temperature, pressure, gas atmosphere) during fission product release, as well as fuel type and burnup. It has not been conclusively shown what would be the main aerosol characteristics. To date, the best summary of aerosol particles formed during severe accidents, partly based on samples from the Phèbus FPT tests, has been given by Kissane [16] showing that " … a particle comprising one-third metal, one-third metal oxide and one-third a mixture of fission-product species would not be out of place in any potential reactor-accident sequence. Particle shapes appear relatively compact without branching chain-like structures. On size and structure, aerosols in the upstream part of the primary circuit would comprise a near-lognormal population with aerosol mass median diameter (AMMD) no more than 2 μm and geometric standard deviation around 2, particles comprising agglomerates of highly-coordinated clusters as small as 0.1 μm". However, as the author points out, the results are based on samples which could have undergone changes before analysis and thereby could have shown different characteristics once air-borne in the reactor coolant system or containment.

In this work, VTT will review experimental data on aerosol characteristics from a series of experiments in VTT FP transport and VTT EXCI-PC facilities, representing conditions in the primary circuit, Figure 6 [17]. It is especially emphasized that particle shape is important in the confined spaces of iPWRs and in filtering devices as it affects particle transport significantly. The aim of this work is to assess the data in relation to the postulated severe accident conditions in both designs 1 and 2.

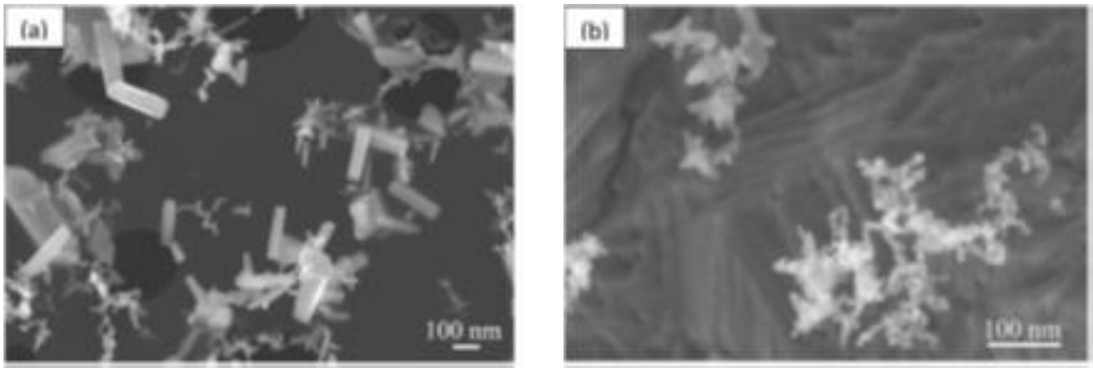

Figure 6. Examples of particle morphology from tests using simulant fission products in the VTT facilities [12].

3.4.2. In-containment source term and hygroscopic aerosol transport

iPWRs rely only on natural circulation and a large amount of water is available to cool the reactor in the case of a malfunction. Thereby it is to be expected that accident conditions are characterized by high steam fractions in the atmosphere. As aerosol particles formed by nucleation and condensation of fission products are often hygroscopic containing, e.g., CsI and/or CsOH, they grow rapidly in the high humidity, condensing atmosphere. The hygroscopic growth can be very fast accelerating the deposition of particles in the containment.

Experiments relevant to transport of hygroscopic aerosols in the condensing atmosphere have been conducted in the AHMED facility at VTT [18]. In the experiments, both hygroscopic and inert Ag aerosols were used, Table 2. It is seen that a shape factor may also have a significant effect on transport of hygroscopic aerosols. It could be noted once the aerosol particle of any shape grows by absorption of water due to hygroscopicity, it is expected that any fractal structures would collapse and they would reach a relatively spherical shape.

Table 2. An example of a comparison of the experimental results with iPWR designs 1 and 2. Data for aerosol transport in the AHMED facility [18].

Parameter	Unit	AHMED	Design 1	Design 2
Relative volume	[-]	1.0	99	2031
Relative diameter	[-]	1.0	2.8	19.7
Relative height	[-]	1.0	16	8.2 + 8.1
Pressure	[MPa]	0.1	> 0.01 – 1.0	0.1 – 1.0
Temperature	[°C]	17-51	15 – 180	15 – tbd
Relative humidity	[%]	7.3-97	Up to 100	Up to 100
D_p	[μm]	2.1-2.7	Sequence analysis	Sequence analysis
GSD	[-]	1.7	Sequence analysis	Sequence analysis
Aerosol material		CsOH, NaOH, CsI, Ag, CsOH+Ag	Mixture	Mixture

Stokes number	[-]	<< 0.1	Sequence analysis	Sequence analysis
Reynolds number	[-]	Not measured	Sequence analysis	Sequence analysis
Shape factor	[-]	1.0	Unknown, could be close to 1	Unknown, could be close to 1

3.4.3. Pool scrubbing of aerosols

With large amounts of water present in the accident situations, it is likely that retention of radioactive compounds by pool scrubbing can be significant in iPWRs for reducing potential release of activity. For example, in design 1, in the case of containment by-pass the radioactive compounds maybe transported to the reactor pool where pool scrubbing would take place.

For assessment of the experimental data for pool scrubbing, synthesis of more than 20 experimental programs on pool scrubbing ranging in time from the 1980's to 2016 has been conducted. Database is built on public access documents including information about the particles, carrier gas, and water pool characteristics [19,20]. Pool scrubbing experimental programs have been qualified in three categories: QfV (Qualified for Validation), UfU (Useful for Understanding), and NU (Not Useful). In the next step, the conditions prevailing in iPWR will be determined, and the comparison between iPWR and large LWR phenomena will be carried out. Applicability of the experimental data to iPWR conditions will then be assessed based on the analysis and comparison, and potential data needs identified.

3.4.4. Iodine chemistry

Iodine being one of the most significant fission products due to its volatility, reactivity and radio-toxicity, it is important to assess its behaviour in iPWRs [21,22,23]. The knowledge of both fission product chemistry, including iodine, and mitigation, e.g., pool scrubbing and porous media filters, will be assessed, and the applicability of the data to iPWRs determined. If new data needs are identified, it is possible to define new experiments to be carried out to generate the missing data.

3.5. Ex-Vessel Cooling and Degradation

iPWRs are designed to be able to cope with any accident conditions without breach of the reactor vessel. However, as it is not yet possible to totally exclude the possibility of a vessel breach, experimental data for ex-vessel phenomena are included in the work in a limited scope. For this, the applicability of the OECD-MCCI and DISCO-L2 experiments will be reviewed and evaluated [24]. Scenario analyses for designs 1 and 2 will be used to determine if ex-vessel phenomena are of significance for iPWRs.

4. SUMMARY

The applicability of existing large LWR severe accident experimental database for two generic iPWR designs is under assessment in SASPAM-SA project. In this work, we have developed a methodology to assess the applicability of the data. Based on DBA and postulated severe accident scenarios for designs 1 and 2, the main boundary conditions and the specific phenomenological features of the two selected iPWR designs are determined. Comparison with experimental data is currently on-going using the main parameters and dimensionless numbers determined based on the governing equations for each phenomenon. Comparison with DBA and severe accident conditions for the iPWR designs 1 and 2 can be done using a table (or plot) in which all the main parameters and, when deemed useful, dimensionless numbers are presented.

The assessment work is divided into four phenomenological areas, namely in-vessel, containment, source term and ex-vessel phenomena. In addition, in this paper natural circulation was presented as its own area due to its importance in the investigated iPWR designs. First results of the assessment work are presented with a description of further work. Classification of the data to applicable, extendable and non-useful will be done to define any further experimental data needs. A close link with the SEAKNOT project will be maintained to include iPWR specific phenomena in the severe accident research roadmap.

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