SAUDI INTERNATIONAL CONFERENCE ON NUCLEAR POWER ENGINEERING

Proceedings of SCOPE
13-15 Nov. 2023 – KFUPM
Paper 23189

THAI database for validation of LWR containment safety analyses codes

Sanjeev Gupta, Martin Freitag, Gerhard Poss
Becker Technologies GmbH, Eschborn, Germany
Email(s): gupta@becker-technologies.com

Abstract – *The present paper provides a synthesis of selected experimental database from national and international (OECD/NEA) THAI projects focused on containment safety of LWRs. Since year 2000, more than 200 experiments have been conducted in 60 m^3 THAI and 80 m^3 THAI$^+$ (extension of THAI in 2015) covering various aspects of containment safety, like thermal-hydraulics, water hydrodynamics, hydrogen risk and fission products distribution behaviour. Experimental investigations also cover investigations related to performance behaviour of mitigation systems employed in light water reactor containments, e.g. BWR suppression pool, passive autocatalytic recombiner and spray. The experimental database facilitating assessment and validation of safety analyses codes towards mitigation, and management of severe accidents is highlighted with emphases on the employed boundary conditions.*

Finally, planned re-orientation of THAI experimental research in the frame of future National THAI and OECD/NEA THEMIS follow-up projects is briefly discussed with emphasis on passive safety systems related investigations including those relevant for water cooled SMRs.

Keywords: THAI, passive safety systems, severe accident, combustion, source term, mitigation, SMRs

I. Introduction

Safety assessment and accident management in nuclear power plants (NPPs) necessitate investigating complex phenomena and processes with adequate accuracy. For this purpose, the severe accident safety analyses codes require to have modelling capabilities to simulate an entire accident sequence starting from the initiating event through to fission product release to the environment ("source term"). To assess credibility of implemented models and to quantify confidence in calculation results to capture diverse aspects of severe accident phenomenology, code/model validation against experimental data is of utmost importance.

Validation efforts are generally extensively taken over by the code developers or code users for specific modelling implemented in their codes, e.g. [1,2]. Moreover, joint activities organised by international agencies, such as OECD/NEA containment code validation matrix [3] provide "common" validation database based on high-ranking phenomena identified through Phenomena Identification and Ranking Tables (PIRT) activities, e.g. [4,5]. Use of commonly agreed validation data also finds application in performing code benchmark exercises facilitating not only assessment of models in different codes but also a common understanding of investigated phenomena towards reactor application. In this regard, international code benchmarks, such as ISP-47 [6] and ISP-49 [7] have provided useful insights on knowledge gaps and the related modelling and experimental research needs.

Experimental facilities play a crucial role in providing suitable validation database. The different scales and design boundary conditions serve the purpose to provide the relevant database for model development/improvement (parametric data) and/or code/model validation (specific boundary conditions). The data requirement may also vary, particularly in terms of tempo-spatial resolution, depending on modelling approaches used, e.g., Lumped Parameter (LP), Computational Fluid Dynamics (CFD), Mechanistic. Different test facilities providing database on separate-effect tests (SET) or coupled-effect tests (CET) are therefore necessary. Integral test facilities are very rare. In some instances, integral tests data may also come from investigations covering an entire accident scenario, e.g., Phebus tests [8]. The database obtained from measurements during or after an accident e.g., TMI-2, Fukushima Daiichi, also fall within category of integral data and may provide a useful basis for validation of safety analyses codes.

The present paper provides a synthesis of selected THAI/THAI$^+$ experiments facilitating assessment and validation of safety analyses tools towards mitigation, and management of severe accidents.

II. THAI EXPERIMENTAL PROGRAMME

THAI research program aims at investigating open questions relevant for safety assessment of water-cooled reactors, with a specific focus on containment safety research under severe accident conditions. Experiments are conducted in the frame of national programme sponsored by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), and international projects which run under the auspices of OECD Nuclear Energy Agency (NEA). Recent experimental activities further broaden the THAI capabilities. For instance, the ongoing THAI national project involves experimental research related to water-cooled small modular reactors (SMRs) by carrying out some provisional arrangements, and the work scope of OECD/NEA THEMIS project includes hydrogen risk and source term related issues with specific focus on late-phase conditions of a severe accident involving CO in addition to H_2 as combustible gases.

The THAI$^+$ facility consist of TTV (60 m^3) and PAD (18 m^3) connected by DN 500 pipes at top and bottom, Fig.1 (left). The extension of original THAI test facility (TTV only) to THAI$^+$ took place in 2015 by installing the PAD vessel connected to the TTV in a loop manner. As required, the tests can be performed in single vessel configuration (TTV or PAD), e.g., SMR tests in PAD as shown in Fig. 1 (right) or in two-vessel configuration (THAI$^+$).

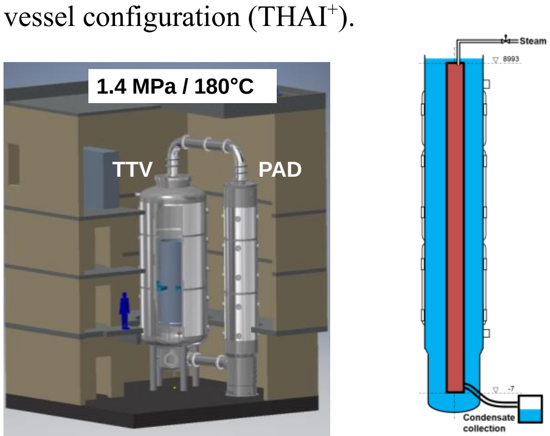


Fig. 1. (Left) THAI$^+$ test facility; (Right) PAD configuration for a SMR test (containment simulator is shown inside PAD). (TTV: THAI test vessel; PAD: Parallel Attachable Drum).

The extended THAI$^+$ test facility has the same design boundary conditions as those in the original THAI test facility, i.e., 14 bar pressure at 180°C and retains its unique experimental features, e.g., use of hydrogen and iodine tracer I-123, and differential wall heating/cooling. To get more details on THAI/THAI$^+$ facility and the associated experimental investigations, one may refer to [9].

III. THAI EXPERIMENTAL DATABASE

III.A. Thermal-hydraulics tests

Majority of the experimental research in containment test facilities available worldwide (e.g., MISTRA, PANDA, TOSQAN, CIGMA) has been conducted using helium due to safety reasons. Transferability of helium-tests to hydrogen distribution in stratified conditions was assessed and confirmed by means of two counter-part tests HM-1 (using helium) & HM-2 (using hydrogen) conducted in the frame of the OECD/NEA THAI project [10].

Aiming for application of thermal-hydraulic database to provide a basis for subsequent combustion and radioactivity carrying fission products transport & distribution analyses, THAI/THAI$^+$ experiments utilise both local and field measurement techniques including optical measurements (e.g., LDA, PIV). The measurements provide detailed data about flow pattern, turbulence, gas velocities, gas concentration and temperature distribution. The data are useful for codes based on different modelling approaches with the necessary tempo-spatial resolution to satisfy the validation requirements of advanced safety analyses tools [11].

Table I describes selected gas distribution and mixing tests conducted in THAI/THAI$^+$ test facility.

Table I THAI/THAI$^+$ gas distribution and mixing tests

Test ID	Conditions	Objectives
HM-1 & HM-2	1.4 bar, N_2/He (or H_2)-steam mixture, 20/55 °C	Verify transferability of He-gas distribution test data to H_2 distribution problems; OECD/NEA code benchmark
TH-13	1.5 bar steam/ air/helium, 20-75 °C	Dissolution of atmospheric stratification, condensate distribution. Used in international standard problem ISP-47

TH-19	1.83 bar, air/steam 90°C	Efficiency of spray systems for cooling of steam containing gas atmosphere; different nozzle diameters and installation locations
TH-22	1.24 bar, air/helium, 40°C (top) & 120°C (middle and lower vessel walls)	Dissolution of air-helium stratification by natural convection, determination of flow field and light gas cloud dissolution time
TH-23	1.0 & 2.0 bar, air or air/steam; 113°C	Condensation of saturated and superheated steam on vessel walls in the presence of non-condensable gas
TH-24	1.5 bar, air/steam, 100°C	Dissolution of a steam-air stratification by natural convection; condensation effect
TH-27	1.0 – 2.5 bar, 22 - 107 °C	First gas distribution test with extended THAI facility (THAI+); double-blind code benchmarking
TH-32	1.24 bar, air/helium 40°C (top) & 120°C (middle and lower vessel walls)	Evaluation of experimental uncertainties in tests with light gas stratifications and their dissolution by natural convection (reference test TH-22)
TH-33	1.24 bar, air/helium/CO_2 40°C (top) & 120°C (middle and lower vessel walls)	Gas-wall radiation effect on gas-mixing when a light gas layer is dissolved by natural convection; data used for code benchmarking

Recently, there has been significant emphasis on quantification and further reduction of uncertainties in severe accident analyses, that also includes exploring new severe accident analysis methodologies in projects like EC-MUSA [12]. To support such activities, the assessment of experimental uncertainties has also been aimed in the THAI test series TH 30-32 with controlled variation in test parameters (e.g., elevation of the helium release) to evaluate the confidence interval of the experimental data. The controlled variation of experimental parameters resulted in about 10% variation in the dissolution time, which facilitated to evaluate modelling uncertainties, which were found to be higher order than experimental uncertainties. Even though blind and open calculations revealed that for a correct prediction of the temperature distribution required appropriate modeling of the heat transfer and the natural circulation in both LP and CFD codes. The modelling of natural convection still needed further improvement, particularly the CFD codes suffered from adequate modelling of the natural convection which had an impact on correct prediction of stratification dissolution [13].

III.B Water pool hydrodynamics (WH)

The experimental research on water hydrodynamics in THAI/THAI+ is oriented towards investigating the fluid-dynamic features produced by a gas/steam discharge in water pools. Considering accident scenarios included postulated loss-of-coolant-accident (LOCA) scenario in a reactor, among others. A broad range of phenomena has been considered as part of experimental investigations, such as complete and incomplete steam condensation, thermal stratification in the water pool, bubble-column induced gas-liquid hydrodynamics, and air blowdown in BWR wetwell to quantify dynamic pressure loadings in pool and wetwell gas space, Table II. In addition to the stand-alone pool hydrodynamic experiments, a number of tests coupled pool hydrodynamic together with fission products retention ("pool scrubbing") and release ("re-entrainment") behaviour. These experiments are discussed in the following sections discussing fission products.

The experimental findings of water hydrodynamic tests have been widely used for analytical activities. As an example, data from blowdown tests WH 16-19 and WH 20-23 test series investigating incomplete steam condensation have been extensively used for assessment and possible refinement of related analytical models, e.g., DRASYS, as sub-model of the containment system code AC^2/COCOSYS [14].

Table II THAI/THAI+ Water pool hydrodynamic tests

Test ID	Conditions	Objectives
WH 1-6	1.0 or 2.0 bar, 10/40/60°C initial water pool temp., steam mass flux (max): 2.4 $kg/m^2.s$	- To study thermal stratification in the wetwell water pool - Stratification break-up by a recirculating spray
WH 7-15	1.0 bar, 10 or 45°C initial water pool temp., air or air-steam injection	Investigation on bubble dynamics in water pool; air or air steam injections
WH 16-20	1.0 bar in vessel gas phase, 10°C initial pool temp., blowdown pressure in pool (using external vessel): 3-10 bars	Blowdown in water pool; dynamic loads in wetwell gas space due to pool swelling, etc.

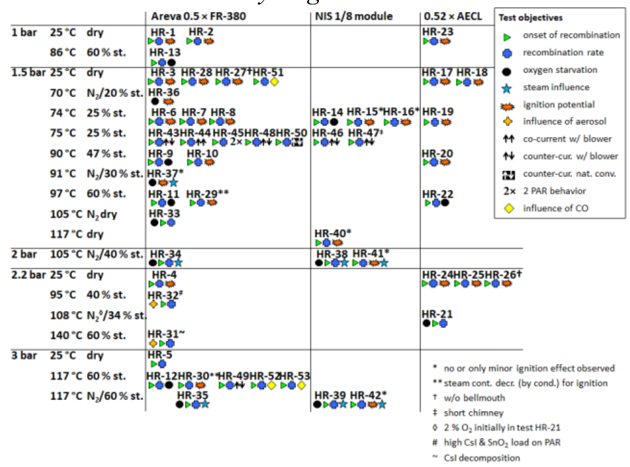
WH 20-23	15-3.0 bar, 70°C initial water pool temp., wall temp. 115°C	Determination of the condensation rate in case of incomplete condensation of steam and steam/air mixture at elevated water temperature.
WH 29-31	1 bar or 3 bars, wall temperature 20°C. Steam injection in water pool through multi-hole sparger.	Investigation on stratification and mixing phenomena in containment pools. Mixing effect for a pump system (WH-29) or a containment typical Sparger (WH 30-31)

III.C Hydrogen Recombination (HR)

Hydrogen recombination by Passive Autocatalytic Recombiners (PARs) is one of the established strategies to mitigate the possible hydrogen risk during design basis or beyond design basis accidents in NPPs. THAI HR tests provide a valuable database both for hydrogen control concept demonstration and code validation purposes by investigating three different commercially available PAR units, namely Framatome/AREVA (Germany), AECL (Canada) and NIS (Germany). The large THAI vessel allows PAR operation with unrestricted natural convection, thus providing database not only on PAR performance (start-up, H_2 depletion, recombination rate), but also on interaction between an operating PAR and vessel (containment) atmosphere, such as effect of gasborne fission products and MCCI conditions (O_2-lean, CO effect, etc.).

Table III provides the test matrix for the THAI HR tests. The PAR test matrix has been further extended in the frame of ongoing OECD/NEA THEMIS project. Five additional experiments have been conducted to provide database to validate PAR models and vendor correlations under late phase conditions (e.g., CO, CO_2, steam, O_2-lean conditions). The tests were conducted at elevated pressure and temperature conditions (four tests at 3 bar/117°C and one test at 4.5 bar/135°C). One of the tests was aimed to study the start-up and performance of a PAR being exposed to deuterium instead of hydrogen gas, as it might typically occur in Heavy Water Reactors, e.g. CANDU or Pressurized Heavy Water Reactors.

Table III THAI/THAI$^+$ hydrogen recombiner tests



			Areva 0.5 × FR-380	NIS 1/8 module	0.52 × AECL
1 bar	25 °C	dry	HR-1 HR-2		HR-23
	86 °C	60 % st.	HR-13		
1.5 bar	25 °C	dry	HR-3 HR-28 HR-27† HR-51		HR-17 HR-18
	70 °C	N_2/20 % st.	HR-36		
	74 °C	25 % st.	HR-6 HR-7 HR-8	HR-14 HR-15* HR-16*	HR-19
	75 °C	25 % st.	HR-43 HR-44 HR-45 HR-48 HR-50	HR-46 HR-47‡	
	90 °C	47 % st.	HR-9 HR-10		HR-20
	91 °C	N_2/30 % st.	HR-37*		
	97 °C	60 % st.	HR-11 HR-29**		HR-22
	105 °C	N_2 dry	HR-33		
	117 °C	dry		HR-40*	
2 bar	105 °C	N_2/40 % st.	HR-34	HR-38 HR-41*	
2.2 bar	25 °C	dry	HR-4		HR-24 HR-25 HR-26†
	95 °C	40 % st.	HR-32#		
	108 °C	$N_2^{◊}$/34 % st.			HR-21
	140 °C	60 % st.	HR-31~		
3 bar	25 °C	dry	HR-5		
	117 °C	60 % st.	HR-12 HR-30** HR-49 HR-52 HR-53		
	117 °C	N_2/60 % st.	HR-35	HR-39 HR-42*	

Test objectives: onset of recombination; recombination rate; oxygen starvation; steam influence; ignition potential; influence of aerosol; co-current w/ blower; counter-cur. w/ blower; counter-cur. nat. conv.; 2× 2 PAR behavior; influence of CO

* no or only minor ignition effect observed
** steam cont. decr. (by cond.) for ignition
† w/o bellmouth
‡ short chimney
◊ 2 % O_2 initially in test HR-21
\# high CsI & SnO_2 load on PAR
~ CsI decomposition

In addition to PAR performance testing under a broad range of thermal-hydraulic conditions, effect of gasborne fission products on PAR performance behaviour has also been investigated in two specific tests HR-31 and HR-32 conducted as part of OECD/NEA THAI project [10]. The tests provide useful insights on conversion of metal iodides to gaseous iodine, and possible poisoning of wet catalysts by aerosol deposition. Together with other THAI tests, test HR-31 is also part of the OECD/NEA CCVM [3]. Considering the high relevance for source term, one experiment (HR-59) is currently under planning in the frame of OECD/NEA THEMIS project with an aim to investigate interaction of a PAR loaded with fire aerosols with gas borne iodine-oxides (IO_x) in a H_2/CO containing atmosphere.

Post-Fukushima accident, there has been significant focus on assessing PAR modelling under late-phase conditions. This subject has also been part of THAI tests and the analytical activities related to hydrogen recombination under oxygen lean conditions were mainly directed towards refinement of PAR modelling and the associated code validation activities. As the tests data were relevant both for PAR-specific performance and interaction of an operating PAR with the surrounding containment gas atmosphere, the analytical activities also benefited from data suitable to validate PARs based H_2-risk mitigation systems performance in full containment analyses. On the subject of PAR performance under O_2-lean conditions, the blind code benchmark conducted in the frame of OECD/NEA THAI-2 project based on test HR-35 [15] revealed that safety analyses codes using "PAR-correlations" overestimate the recombination at the beginning of the experiment (oxygen starvation conditions). All code calculations improved during open simulation phase (modelling improvements, e.g. modified vendor correlation, modified calibration of modelling constants, inclusion of thermal radiation effect). In the recently held code benchmark based on test conducted at 4.5 bar pressure in OECD/NEA THEMIS framework revealed that approaching condition of oxygen starvation at high pressure yields a complex interaction between reduction of hydrogen recombination and continuation of carbon monoxide recombination at very small rate in the test. The observed modelling deficiencies under these boundary conditions are under consideration by the participating organizations.

III.C Hydrogen Deflagration (HD)

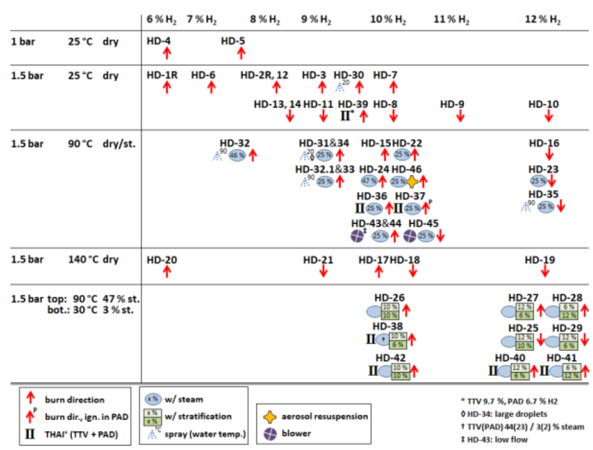
A fundamental understanding of hydrogen deflagration behaviour in large scale test facility is necessary for safety assessment, e.g., impact of the resulting pressure/temperature loads on containment integrity, potential degradation of safety components by deflagration. Furthermore, high temperature and turbulence generated by deflagration may have an impact on fission products speciation and their location due to remobilization. In this context, the objective of THAI deflagration experiments, which are generally limited to slow-deflagration regime due to safety reasons, is to provide data for an improved understanding of hydrogen combustion phenomena and also to deliver validation database for safety analyses codes. Nevertheless, in contrast to single-vessel THAI tests, flame acceleration was observed in THAI+ test facility at hydrogen concentration of about 6 vol. %, which occurred inside the lower and upper DN500 connecting pipes and resulted into instantaneous ignition of unburnt mixture and flame acceleration (several tens of m/s) from upper connecting pipe in the downward compartment but the generated temperature/pressures remained well within facility design conditions.

Table IV provides a list of THAI deflagration experiments together with details on the specified test conditions. The systematic variation of the test parameters and test conditions, i.e. initial pressure, initial temperature, vertical temperature gradient, hydrogen concentration (homogeneous and stratified), steam concentration (homogeneous and stratified), burn direction (upwards and downwards) help to determine the influence of these parameters on combustion behaviour.

Combustion tests conducted in THAI/THAI+ facility also aim to investigate deflagration induced effects on source term related issues, e.g., iodine and aerosol behaviour. One of such effects is related to fission products remobilisation behaviour, which may occur due to resuspension of pre-deposited fission products by hydrogen deflagration ("delayed source term"). The remobilisation of fission products is considered to be a high priority topic at international level in the light of Fukushima accident, e.g. in case of venting of containment atmosphere [16]. The hydrogen deflagration tests in THAI/THAI+ designed to investigate aforesaid issues are described later on in this paper within the sections on "Fission products behaviour".

In addition to phenomenological insights, THAI/THAI+ tests aim to provide data for development and to validate simulation models which are capable of predicting the peak pressures and temperatures but also the distribution of heat among gas and structures (including painted surfaces) after the deflagration.

Table IV THAI/THAI+ hydrogen deflagration tests



The tests data have also been extensively used for analytical activities. The recent simulation benchmark was based on test HD-44 and included both blind and open calculation phases [17]. The code benchmark aimed to investigate the influence of initial convection flows on the hydrogen combustion in a two-vessel configuration and the relevance of scale for flame acceleration effect as a function of the hydrogen concentration in the THAI+ facility. Compared to the tests without initial convection only very few simulations were capable to predict a much faster flame propagation in the blind simulation of the test

HD-44. This is contributed either due to an under-prediction of the turbulence level introduced by the blower or a lack of chemistry-turbulence interaction in the models [17].

III.D Fission products behaviour – gaseous iodine

Iodine experiments in THAI/THAI$^+$ aim to investigate the interaction of gaseous iodine (e.g. physisorption, chemisorption) with (stainless) steel surfaces and painted surfaces (artificially aged decontamination paint). Apart from surface interaction tests, gaseous iodine interaction with gasborne aerosols, water pools under different thermal-hydraulics and chemical boundary conditions (e.g., sub-cooled to boiling pools, pH effect) have also been subject of the THAI experimental research. The tests provided new quantitative data from large-scale experiments about deposition/resuspension velocities, reaction rate coefficients, iodine mass transfer to/from water pool and wash-down efficiencies for both steel and painted surfaces. Table V provides a list of gaseous iodine distribution tests conducted in THAI/THAI$^+$.

Table V THAI/THAI$^+$ gaseous iodine distribution tests

Subject	THAI tests
Iodine mass transfer	Iod-9: the mass transfer of molecular I_2 from the gas into sump, and the iodine transport into the sumps during condensing conditions at the walls Iod-23: Mass transfer of molecular iodine at the water pool-gas interface as a function of water motion has been investigated in THAI test Iod-23.
Multi-compartment iodine behaviour to investigate I_2 /surface interaction under different thermal-hydraulic conditions (*rh = relative humidity*)	Iod-10: dry conditions (rh ≈10 %), steel; Iod-11: dry conditions, high rh (90 %), steel; Iod-12: wet conditions (steam inj.), steel; Iod-19: repetition of Iod-11; Iod-27A: painted area, dry conditions (rh < 10%); Iod-28: painted area, dry conditions, high rh (90%); Iod-30: painted area, high rh (90%), Ag-aerosol Iod-33 and Iod-35: Iodine behaviour in room-chain configuration in superheated and saturated steam atmosphere.
I_2 interaction with airborne aerosols	Iod-25: non-reactive aerosols (SnO_2); Iod-26: reactive aerosols (Ag)
I_2/air radiolysis product (Ozone) interaction	Iod-13: I_2 release followed by ozone injection. Iod-14: Ozone release followed by I_2 injection.
I_2 removal from painted surfaces by condensing steam	Iod-21: Washdown of I_2 pre-deposited on dry painted surfaces Iod-24: Simultaneous deposition and removal of I_2 from painted surfaces, low and high steam mass flux, effect of surface drying on iodine resuspension.
Iodine flashing	Iod-29, DBA scenario of SGTR. High temperature iodine chemistry.
Iodine removal from containment atmosphere by spray	Iod-31: Influence of fresh water spray and I_2-dissolved recirculated water spray on I_2 washout behaviour, pH effect
Iodine release from water pools	Iod-32: Volatile Iodine Release from Boiling Water Pool at Elevated Temperature, pH effect
Iodine resuspension from painted surfaces	Iod-34: Resuspension of pre-loaded gaseous iodine on painted surfaces by H_2 deflagration. Measurement of released amount and iodine speciation.

The two THAI tests on the I_2/aerosol reactions (Iod-25, Iod-26) provided the effect of I_2 removal from containment atmospheres by interaction with containment aerosol, the reactive Ag aerosol providing the maximum reactivity, and the inert SnO_2 the minimum reactivity under the given boundary conditions of the tests. The I_2 reaction with the Ag particle surface was found to be as high as for the higher range of I_2 /paint reactions. Real containment aerosol mixed of different materials can be expected to exhibit I_2 removal rates between the investigated bounding cases "reactive Ag" and "inert SnO_2". The Iod-25 and Iod-26 tests data have been extensively used for modelling work, e.g. estimation of gaseous iodine adsorption velocity on aerosols derived based on tests data for application in BWR severe accident analyses with ART code [18]. Regarding high temperature iodine chemistry, the iodine flashing test Iod-29 demonstrated that codes had difficulty in matching the experimental observation that the injected molecular iodine reacted quickly with the steel wall of the primary vessel during heat-up and thus, had produced the non-volatile iodide form. More experimental and analytical work has been considered necessary in future to accurately account for on aqueous phase iodine chemistry effect in source term calculations.

III.D Fission products behaviour – Aerosols

During a core meltdown accident, radioactive fission products are released from the fuel elements and carried into the containment. In order to assess the potential radioactivity releases from the containment to the environment, the behaviour of the fission products in the containment needs to be known. Since most of the important radionuclides are present in the form of aerosols, aerosol deposition or resuspension behaviour can affect the release of radioactivity to the atmosphere. The behaviour of the aerosol particles, like agglomeration, deposition on walls, and advective transport, is dependent upon the thermal hydraulic conditions in many aspects. A substantial step towards more realistic conditions is provided by the THAI/THAI$^+$ aerosol distribution experiments. The size of the facility allows studying the combined effects of physical advection-dispersion in the atmosphere, mass exchanges at walls and water surfaces, and chemical reactions with structural surfaces or materials dissolved in water. Selected THAI/THAI$^+$ aerosol tests are reported in Table VI.

Table VI THAI/THAI$^+$ aerosol distribution tests

Subject	THAI tests
Aerosol remobilization	AER-1, AER-3 and AER-4: Dry suspension of pre-deposited CsI aerosols by H_2-induced high-flows. HD-46: resuspension of CsI aerosols pre-deposited on vertical, horizontal and containment typical grating surfaces. Generation of I_2 due to CsI thermal decomposition
Aerosol removal from surfaces by condensing steam	AW: Test with soluble aerosol (CsI) AW-2: Test with aerosol mixture (CsI/SnO_2) AW-3: Test with reactive aerosol (Ag) AW-5: SnO_2/CsI mixture depletion in condensing atmosphere
Re-entrainment from water pools	WH-24: Re-entrainment of soluble fission product CsI from water pools at elevated temperature; WH-28 additionally investigate the effect of (impurities) on the re-entrainment of CsI from the pool
Removal by Spray	AW-4: Removal of gasborne CsI aerosols by injecting spray at two different times (particle size effect on washout behaviour)
Pool scrubbing	WH 25-27: Decontamination factors for SnO_2 aerosol (BWR suppression pool configuration); bubble flow regime WH 30-34: Decontamination factors for SnO_2 aerosol ; transition to the jet injection regime: test data of WH-33 used for a code benchmark

The experimental series on aerosol washdown provided relevant database for development of aerosol washdown modelling in GRS code AC^2/COCOSYS by using THAI aerosol washdown tests data [19]. Compared to initial three tests (AW, AW-2 and AW-3) investigating washdown of dry deposited aerosols, test AW-5 addressed the aerosol depletion and removal both under condensing conditions including statistical evaluations of the rivulet behaviour at surfaces with different inclinations. The test was accompanied by a laboratory test series to test and qualify the aerosol injection device used for generating multi-component aerosol. Data are useful for investing aerosol depletion and deposition behaviour under natural convection, e.g. aerosol remobilization behaviour inside submerged containments of specific LW-SMRs designs [20].

IV. Conclusions and Perspectives

The THAI/THAI$^+$ experiments cover a wide range of containment safety related issues under severe accident conditions. The database also includes investigations on performance behaviour of engineered safety and mitigation systems, such as Spray, PARs, BWR suppression pool, under a broad range of accident conditions. Some of the remaining open issues related to hydrogen and fission products relevant for the current fleet of LWRs are being investigated in the ongoing national and the OECD/NEA THEMIS projects. The ongoing THEMIS project focuses on severe accident “late phase” conditions, e.g., reduced O_2 concentrations, presence of CO, upto 70 vol.% steam, representative fission products. Topics related to combustible gas in THEMIS project include hydrogen/carbon monoxide combustion and PAR performance behaviour and the source term related investigations include pool scrubbing under jet-regime, iodine oxide behaviour under high temperature condition and its interaction with other nuclear aerosols. The ongoing national project (Phase VII) which aims to provide database on hydrogen risk and source term related issues for current fleet of reactor also covers thermal-hydraulic issues oriented towards water-cooled small modular reactors, e.g. experiments on passive heat removal of immersed containments by turbulent convection at very high Rayleigh numbers [21].
As a future perspective, in addition to current fleet of reactors, experiments needed for safety assessment of LW-SMRs are being discussed in the framework of OECD/NEA THEMIS follow-up and future national

project (both currently under preparation phase) and planned to be adequately addressed in the THAI+ facility. In order to address these topics with adequate dimension, the facility is planned to be extended in near future.

Acknowledgments

THAI experimental research program is funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), on the basis of a decision of the German Bundestag. The sponsorship by the countries participated in the concluded OECD/NEA THAI, THAI-2. THAI-3 projects and the ongoing THEMIS project is gratefully acknowledged.

References

1. P. Chatelard and L. Laborde, “Synthesis of the ASTEC V2.2 code validation against experimental data”, The 10th European Review Meeting on Severe Accident Research (ERMSAR2022) Akademiehotel, Karlsruhe, Germany, May 16-19 (2022).
2. H.-J. Allelein, S. Arndt, W. Klein-Heßling, S. Schwarz, C. Spengler, G. Weber, “COCOSYS: Status of development and validation of the German containment code system”, Nuclear Engineering and Design, Vol 238, Issue 4, pp 872-889 (2008).
3. OECD/NEA, “Containment Code Validation Matrix”, Nuclear Safety NEA/CSNI/R(2014)3 May (2014).
4. D. Magallon, et al., European expert network for the reduction of uncertainties in severe accident safety issues (EURSAFE), Nuclear Engineering and Design, Vol. 235, Issues 2–4, pp 309-346 (2005).
5. W. Klein-Heßling, et al., “Conclusions on severe accident research priorities”, Annals of Nuclear Energy, Vol. 74, pp 4-11 (2014).
6. H.-J. Allelein, K. Fischer, J Vendel et al. “International Standard Problem ISP-47 on Containment Thermal Hydraulic”. Report NEA/CSNI/R(2007)10 (2007).
7. NEA, “ISP-49 on Hydrogen Combustion”, Nuclear Safety NEA/CSNI/R(2011)9, January (2012).
8. B. Clément, R. Zeyen, “The objectives of the Phébus FP experimental programme and main findings”, Annals of Nuclear Energy, Vol. 61, pp 4-10 (2013).
9. S. Gupta, M. Freitag, G. Poss, “THAI experimental research on hydrogen risk and source term related safety systems”, Front. Energy 15, 887–915 (2021).
10. OECD/NEA, “Summary report of the OECD/NEA THAI Project: Hydrogen and Fission Product Issues Relevant for Containment Safety Assessment under Severe Accident Conditions”, NEA/CSNI/R(2010)3, June (2010).
11. S. Gupta, B. von Laufenberg, M. Freitag, M. Colombet, E. Schmidt, G. Poss, G. Langrock, F. Funke, “Instrumentation for LWR containment experiments under accident conditions”, In: Proceedings of Specialist Workshop on Advanced Instrumentation and Measurement Techniques for Nuclear Reactor Thermal Hydraulics (SWINTH-2016), paper no. 043, Livorno, Italy, June 15-17 (2016).
12. L. E. Herranz, S. Beck, V. H. Sanchez-Espinosa, F. Mascari, S. Brumm, O. Coindreau, S. Paci, “The EC MUSA project on management and uncertainty of severe accidents: main pillars and status”. Energies, 14(15), 4473 (2021).
13. M. Freitag, E. Schmidt et al., Simulation benchmark based on THAI-experiment on generation and dissolution of a light gas stratification by natural convection, At 19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-19) Brussels, Belgium, August 29 - September 3, 2021
14. W. Klein-Heßling et al., “COCOSYS V1.2 Programme Reference Manual”, Report GRS-P-3/2, July (2000)
15. M. Freitag et al., “CFD and LP code benchmark evaluating the onset of PAR operation in case of extremely low oxygen concentration”, Nuclear Engineering and Design, Vol. 400 (2022).
16. NEA, “Status Report on Filtered Containment Venting”, NEA/CSNI/R(2014)7, July (2014).
17. M. Freitag, M. Sonnenkalb, “Comparison Report for Blind and Open Simulations of HD-44. Hydrogen combustion and flame propagation in two-compartment system with initial convective flow”. Report No. 1501516-CR-HD44, Becker Technologies GmbH, Eschborn, Germany, September (2019).
18. J. Ishikawa, H. Itoh, Y. Maruyama, “Influence of adsorption of molecular iodine onto aerosols on iodine source term in severe accident”, Proceedings of ICONE-23 conference (2015).
19. G. Weber, F. Funke, W. Klein-Hessling, S. Gupta, “Iodine and silver wash-down modelling in COCOSYS-AIM by use of THAI results”, International Iodine Workshop Summary Report, Nuclear Safety NEA/CSNI/R(2016)5 (2016).
20. L. Lebel, A. Morreale, K. Batten, T. Clouthier, “Aerosol retention within submerged Containment-Type iPWRs: Experiments and modeling”, Nuclear Engineering and Design, Vol 398 (2022).

M. Freitag, E. W. Schmidt, B. von Laufenberg, S. Gupta, “Experiments on Passive Heat Removal of Immersed Containments by Laminar and Turbulent Convection at Very High Rayleigh Numbers”, Proceedings of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20) Washington, D.C., August 20–25 (2023).