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Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Experiments Related to Nuclear Reactor Thermal Hydraulics and Severe Accidents (SWINTH-2019)

Summary Report

22-25 October 2019
Livorno (Italy)

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Acknowledgements

The member countries of the Nuclear Energy Agency (NEA) and the participants in SILENCE (Significant Light and Heavy Water Reactor Thermal-hydraulic Experiments Network for the Consistent Exploitation of the Data) Network, the NEA Committee on the Safety of Nuclear Installations (CSNI) and the NEA Working Group on the Analysis and Management of Accidents (WGAMA) wish to acknowledge the significant contributions of those individuals who had a key role in the preparation of the summary report, and those who had a leadership role in conducting the NEA Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Experiments Related to Nuclear Reactor Thermal Hydraulics and Severe Accidents. These individuals include the members of the Organising Committee: Nusret Aksan (Chair), Dominique Bestion, Luis Enrique Herranz, Didier Jacquemain, Nils Sandberg, Hideo Nakamura and Fabio Moretti. Mr Moretti, of Nuclear and Industrial Engineering S.r.l., is also thanked for his contribution to organising the workshop and preparing this summary.

The workshop was sponsored by HZDR Innovation, Mc Master University, A2 Photonic Sensors and Becker Technologies GmbH. Their financial support and their technical-scientific contribution are gratefully acknowledged.

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Executive summary

The Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Experiments Related to Nuclear Reactor Thermal Hydraulics and Severe Accidents (SWINTH-2019) was held in Livorno, Italy, on 22-25 October 2019. It was co-organised by the SILENCE (Significant Light and Heavy Water Reactor Thermal-hydraulic Experiments Network for the Consistent Exploitation of the Data) Network, the Nuclear Energy Agency (NEA), the NEA Committee on the Safety of Nuclear Installations (CSNI) and the NEA Working Group on the Analysis and Management of Accidents (WGAMA), and hosted by the University of Pisa. The aim of the meeting was to provide an opportunity for the thermal hydraulics (TH) and severe accident (SA) communities to meet, discuss and share the latest advancements in the area of instrumentation and measurement techniques for TH experiments relevant to nuclear reactor technology and safety.

The meeting followed the first SWINTH workshop, also held in Livorno, Italy, on 15-17 June 2016, and organised by the SILENCE Network. It represented the first international specialist meeting on the subject after the NEA meeting held in Santa Barbara, California, United States, in 1997. Compared to earlier meetings, SWINTH-2019 had a wider scope, which included SA-relevant TH experimentation.

The workshop was structured as follows:

- five keynote (KN) lectures plus a "special presentation" (50 minutes each, including time for Q&A);
- 36 oral presentations of technical papers by the authors (25 minutes each, including time for Q&A);
- a summary session / open discussion at the end of the workshop;
- a session devoted to sponsors' presentations, on the first day.

The selection of the five keynote lecturers aimed to involve high-level international experts through connections with the NEA and SILENCE, to achieve a relatively wide geographical representation (Asia, Americas, Europe), and to cover both TH and SA areas. The invited lecturers could select the topics of their keynotes without constraints other than the connection to the scope of the workshop.

The keynote lectures were:

1. "High-fidelity experimental measurements for modelling and simulation of nuclear engineering applications" (Prof. Yassin Hassan, Texas A&M University, United States);
2. "Practical science of 'revitalizics' for decommission of Fukushima Daiichi Nuclear Power Plant - Innovation with ultrasonic measurement and robotic system" (Prof. Hiroshige Kikura, Tokyo Institute of Technology, Japan);

3. "Advanced instrumentations for nuclear thermal hydraulic experiments in Korea" (Prof. Byongjo Yun, Pusan National University, Korea);
4. "Experimental study on the heat flux of a heat exchanger for passive cooling of spent fuel pools by temperature anemometry grid sensor" (Mr Sebastian Unger, Helmholtz-Zentrum Dresden-Rossendorf, Germany);
5. "Outcomes of the OECD/NEA Hydrogen Mitigation Experiments for Reactor Safety **(**HYMERES**)** Project" (Dr Domenico Paladino, Paul Scherrer Institute, Switzerland).

The "special presentation" was given by Dr Dominique Bestion and concerned "Reporting about WGAMA & SILENCE activities on requirements for validation experiments". The 36 paper presentations were divided into the following eight technical sessions (four of which were split into two parts), classified by instrumentation technologies or type of investigation:

- I-1 & I-2: Special or combined experimental techniques; SA-specific [7 papers];
- II-1 & II-2: Conductivity and impedance methods – wire mesh sensors [7 papers];
- III: Particle Image Velocimetry (PIV); Laser Doppler Anemometry (LDA); Laser Induced Fluorescence (LIF) [4 papers];
- IV-1 & IV-2: Local single- and multi-sensor probes [5 papers];
- V: Flow visualisation methods [4 papers];
- VI: Thermal anemometry and anemo-thermometry [2 papers];
- VII-1 & VII-2: Radiographic and tomographic methods [5 papers];
- VIII: Pressure-based measurements [2 papers].

A summary session was held at the end of the workshop, which allowed further discussion on specific topics and issues that emerged during the technical sessions, collecting the participants' feedback on the workshop, the chairpersons' evaluation and a synthesis of the respective sessions. For instance;

- elements of novelty and innovation were recognised in several presentations, which showed how improved measurement techniques, or the combined use of existing technologies, could bring new insights into two-phase heat and mass transfer processes;
- some of the presented work showed significant effort and original approaches to perform measurements in SA experiments and overcome related difficulties;
- while there was increased attention to the quantification of measurement uncertainty compared to the previous SWINTH workshop, many presentations and papers still lacked uncertainty-related information;
- various useful information was collected about limitations, margins for improvement, and current and potential use of specific measurement techniques;
- for some measurement techniques, specific recommendations could be drawn;
- participants' feedback on organisational aspects was gathered, and will be considered for the organisation of the next SWINTH workshop.

The sponsors session consisted of short presentations given by the sponsors' delegates to provide information on relevant R&D activities in their organisations or companies.

Overall, 64 participants attended the workshop of which 39 came from Europe, 21 from Asia and 4 from North America.

The second SWINTH workshop attracted a high-quality community of experimentalists in thermal hydraulics related to design basis accident (DBA) and severe accident analyses. According to a questionnaire, attendees appreciated the quality of the invited papers, technical sessions and discussions. After thorough consideration, some of the papers were selected for journal publication. One may summarise the overall highlights as follows;

- novelties and progress were reported for many instrumentation techniques;
- the importance of the analysis of sources of measurement errors and of the quantification of accuracy and uncertainties was emphasised.

As a result, some lessons learnt during the workshop helped update the state of the art and formulate recommendations, in particular to continue efforts in the area of measurement uncertainty quantification by assessing the state of the art and promoting the systematic use of existing guidelines and the development of new, more specific guidelines where needed.

List of abbreviations and acronyms

AFVL	Association Francophone de Vélocimétrie Laser (French-speaking Association of Laser Velocimetry)
AIVELA	Associazione Italiana Velocimetria Laser (Italian Association of Laser Velocimetry)
BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium (Canadian-type pressure tube heavy water reactor)
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (Alternative Energies and Atomic Energy Commission, France)
CFD	Computational fluid dynamics
CHF	Critical heat flux
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Center for Energy, Environmental and Technological Research, Spain)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DBA	Design basis accident
ECC	Emergency core cooling
EDS	Energy dispersive X-ray spectroscopy
EIT	Electrical impedance tomography
FCI	Fuel-coolant interaction
GUM	Guide to the Expression of Uncertainty in Measurement (ISO)
IR	Infrared
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Institute of Radiological Protection and Nuclear Safety, France)
ITF	Integral test facility
JAEA	Japan Atomic Energy Agency
KN	Keynote
LDA	Laser Doppler Anemometry
LDV	Laser Doppler Velocimetry
LWR	Light water reactors
MASCA	Material scaling

MBP	Maximum bubble pressure
NEA	Nuclear Energy Agency
OC	Organising Committee
ONB	Onset of Nucleate Boiling
OSV	Onset of Significant Void
PWR	Pressurised water reactors
ROCOM	Rossendorf Coolant Mixing Mode
SA	Severe accident
SC	Scientific committee
SILENCE	Significant Light and Heavy Water Reactor Thermal-hydraulic Experiments Network for the Consistent Exploitation of the Data
STGR	Steam generator tube rupture
SWINTH	Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Experiments Related to Nuclear Reactor Thermal Hydraulics and Severe Accidents (NEA)
TH	Thermal hydraulics
UQ	Uncertainty quantification
WGAMA	Working Group on the Analysis and Management of Accidents (NEA)
WMS	Wire-mesh sensors
WS	Workshop

1. Introductory remarks on SWINTH-2019

1.1. Background, objectives and scope of the workshop

Compared to a previous workshop in 2016, the 2019 edition of the Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Experiments Related to Nuclear Reactor Thermal Hydraulics and Severe Accidents (SWINTH-2019) featured two novelties: the involvement of the Working Group on the Analysis and Management of Accidents and the extension of the scope to thermal-hydraulic experiments related to severe accidents (SA).

The scope of the workshop included the following topics and aspects:

- water cooled nuclear reactor accident phenomena: defence-in-depth level one through four;
- the scale and complexity of experiments and phenomena: from basic to separate and integral effect tests to investigate any phenomena of postulated accidents;
- purpose of the experiments: understanding of phenomena and processes for an accident and its analysis, support for model development and code validation, and safety demonstration;
- types of measurement techniques; local and/or space-averaged instantaneous and/or time-averaged quantities of single-phase and/or multi-phase/multi-component flows, fields and structures/materials, with sufficiently fine resolution and uncertainty quantification, e.g. visualisation techniques and optical, radiographic and tomographic methods to measure temperature, pressure, velocity, void, chemical and phase composition, detection of radiation/fission products and fissile materials; fission product speciation;
- innovation in measurement techniques/methods and/or their application;
- possible use of simulant fluids with well-established scaling laws;
- correspondence between experimental techniques, resulting measurement and applicability to different code types (i.e. system TH, sub-channel analysis, computational fluid dynamics [CFD], containment TH and SA);
- fluid-structure interaction, molten-core-coolant interaction and molten-core-structure interaction;
- gaps between current model/code validation needs and existing technology; definition of requirements for new experiments and instrumentation, also in terms of “quality” of data;
- measurement uncertainty evaluation depending on type of instruments and measurement method with possible influence of TH and/or SA phenomena to simulate;
- issues related to the handling and preservation of experimental data;

- specifically concerning instruments for SA-related experiments: major challenges and solutions, improvements and advancements being proposed, under development and/or already in use, including in light of lessons learnt from the Fukushima Daiichi accident.

Another initiative inspired by the SWINTH workshops of 2016 and 2019 is the NEA Specialist Workshop on Advanced Measurement Method and Instrumentation for Enhancing Severe Accident Management in a Nuclear Power Plant Addressing Emergency, Stabilisation and Long-term Recovery Phases (SAMMI-2020), held on 7-10 December 2020 in the form of an online conference. This workshop specifically addressed severe accident management-related nuclear power plant instrumentation, thus complementing the scope of SWINTH-2019.

1.2. Organisation, programme and structure

An Organising Committee (OC) took care of the planning and organisation of the meeting on behalf of the SILENCE Network and the WGAMA. The OC members are:

- Nusret Aksan (Chair of the Organising Committee)
- Dominique Bestion (Chair of the workshop)
- Luis Enrique Herranz (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas [CIEMAT], Spain)
- Didier Jacquemain (Institut de radioprotection et de sûreté nucléaire [IRSN], France)
- Fabio Moretti (Nuclear and Industrial Engineering S.r.l. [NINE] and University of Pisa, Italy) – Co-ordinator of organisation works
- Hideo Nakamura (Japan Atomic Energy Agency [JAEA])
- Nils Sandberg (NEA)

The University of Pisa, with the support of NINE, was in charge of hosting the event and of the local organisation.

A scientific committee (SC), composed of 23 people including the OC members, was involved in the definition of the technical programme of the workshop and in the paper review process. The latter task benefited from the support of a number of additional experts, for a total of about 40 reviewers.

The above mentioned “special presentation” was given by Dr Dominique Bestion and consisted of “Reporting about WGAMA & SILENCE activities on Requirements for Validation Experiments”.

The 36 paper presentations were divided into eight technical sessions (four of which were split into two parts), classified by instrumentation technologies or type of investigation. There were no parallel sessions, in order to give the participants the possibility to attend all the presentations. There were no poster sessions either.

The technical sessions are listed in Table 1.1.

The summary session was meant to collect participant feedback and impressions on the workshop and the session chairpersons’ evaluation and synthesis of the respective sessions as well as to allow discussions on topics and issues that may have emerged during the workshop. The present report takes those outcomes into account.

The sponsors session consisted of short presentations given by the sponsors' delegates to provide information on relevant R&D activities in their organisations or companies.

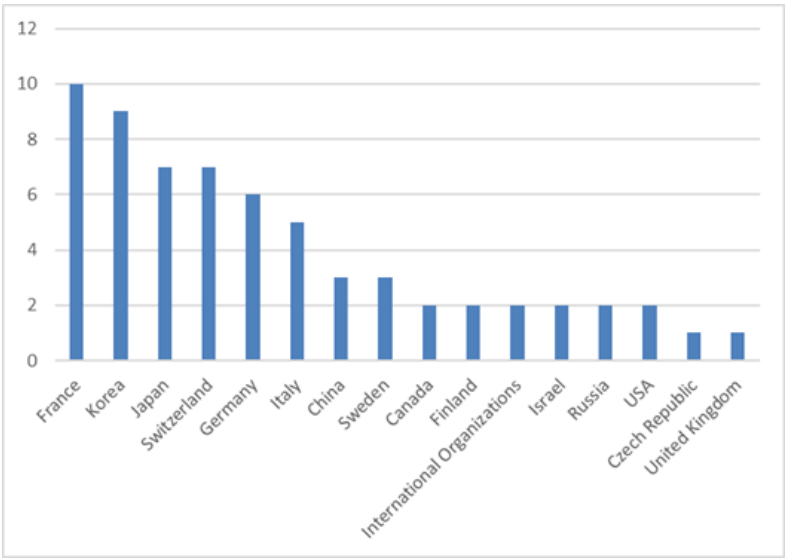
Table 1.1. Technical sessions

Session ID	Technical session title	No. of papers
I-1	**Special or combined experimental techniques, SA-specific** e.g. aerosol removal.	3
I-2		4
II-1	**Conductivity and impedance methods – wire mesh sensors**	3
II-2		4
III	**PIV - LDA and LIF**	4
IV-1	**Local single- and multi-sensor probes** (optical probes, conductance probes, temperature probes), including optical fibre probes for phase detection and temperature measurement.	3
IV-2		2
V	**Flow visualisation methods** including high-speed cameras and infrared methods, for liquid film thickness and temperature measurement, holographic methods, etc.	4
VI	**Thermal Anemometry and Anemo-Thermometry** including hot-wire and hot-film sensors.	2
VII-1	**Radiographic and tomographic methods** including X-rays, gamma-rays, neutrons, and electrical impedance tomography.	3
VII-2		2
VIII	**Pressure-based measurements**	2

1.3. Attendance

Sixty-four participants attended the workshop. All of them were male. Statistics on geographical origin are shown in Figure 1.1.

Figure 1.1. Geographical origin of SWINTH-2019 participants



2. Chairperson's synthesis and evaluation of technical sessions

The chairperson of each technical session was asked to draft a short evaluation and synthesis report of the session based on the written papers, presentations and discussions (using a template provided by the organisers), and to present them during the summary session at the end of the workshop.

The active role of the chairperson during the technical sessions, as well as in the conclusive phase, made a thorough evaluation of the technical content of the workshop possible.

This section is based on the written material provided by the chairperson of each session. As they had to provide their contributions in relatively short time, there was not enough time for preliminary exchanges and harmonisation in the evaluation approach, which explains some heterogeneity.

2.1. Session I-1: Special or combined experimental techniques; SA-specific (Part 1)

Session Chair: **Domenico Paladino** (Paul Scherrer Institute, Switzerland)

Presented papers:

Table 2.1. Papers presented in session I-1

#015	Large wall-superheat oscillations in steady, diabatic upward annular flow measured with synchronised IR thermography and liquid film thickness diagnostics
	G.Y. Su, F. P. D'Aleo, B. Phillips, E. Al-Safran, J. Buongiorno and H.M. Prasser ***(M. Bucci)***
#050	Measurement of forced convection subcooled boiling flow and rod surface temperature distribution
	A. Ui, M. Furuya, T. Arai and K. Shirakawa
#057	The use of a novel gradient heat flux sensor for characterisation of reflux condensation
	F. Janasz*, H.M. Prasser, D. Suckow and A. Mityakov*

The interest of novel sensors and of combining several experimental techniques was demonstrated in session I-1 with the following original insights into annular flow, subcooled boiling and reflux condensation:

- Synchronised infrared (IR) thermography and liquid film thickness in heated annular flow [paper #015] has shown oscillations of liquid film thickness and wall temperature, which could lead to thermal fatigue and early dryout even in steady state conditions. The respective effects of material thermal properties and roughness, and of flow velocity, should be further investigated experimentally.

- A thorough characterisation of two-phase convective heat transfer [paper #050], particularly of Onset of Nucleate Boiling (ONB) and Onset of Significant Void (OSV), was presented using optical fibre for the measurement of rod surface temperature, high-speed cameras for the measurement of low void fraction and optical double-sensor probes for the measurement of two-phase flow parameters. Measurement uncertainty was addressed in the paper and discussed during the presentation. A comparison with data from a Seoul National University facility (equipped with four-sensor probes) is planned.
- A novel heat flux sensor [paper #057] made from alternating layers of two materials with different Seebeck coefficients features a noticeably short response time and thus allows faster data acquisition than with traditional heat flux sensors based on thermocouples. Moreover, it is accurate and is relatively small in size. Improvements have been made over the last years on the sensor design and installation procedure to solve robustness and durability issues. This sensor is relevant to reflux-condensation investigation, which is expected to occur in pressurised water reactors (PWR) under certain accident conditions.

2.2. Session I-2: Special or combined experimental techniques; SA-specific (Part 2)

Session Chair: **Nourdine Chikhi** (Commissariat à l'Energie Atomique et aux Energies Alternatives, France)

Presented papers:

Table 2.2. Papers presented in Session I-2

#006	Review of researches using analogy concept for thermal hydraulic and severe accident experiments
	***B.-J. Chung**, M.-S. Chae, J.-Y. Moon and H.-K. Park*
#031	Examination of aerosol removal in steam generator under severe accident condition
	***B. Lee**, S. I. Kim and K. S. Ha*
#052	Fundamental study on application of sonoluminescence to chemical elemental analysis
	***H. Takahashi**, S. S. Nisa Sailellah and H. Kikura*
#053	FASP - Measuring technique for fog droplets and aerosols
	***G. Poss**, H. J. Allelein and M. Frank*

Session I-2 showed original results, methods and innovative approaches in the difficult domain of severe accidents (SAs).

- An original and innovative approach of the analogy between heat and mass transfer was presented by paper #006 which is very relevant to building smart and cheap experiments. The paper proposed many illustrations, including on critical heat flux (CHF) measurement and simulation of molten pool convection.

- A new facility to characterise aerosol deposition during steam generator tube rupture (STGR) was presented (Paper #031). The size of the facility (7 m in height) is to be noticed. Original data were provided.
- A very interesting and innovative technique was presented (paper #052) for measuring the concentration of metal elements into solutions. It had to be tested under irradiated conditions. It is an original approach with various applications.
- A state-of-the-art paper was presented (paper #053) on Fast Aerosol Spectral Photometer (FASP) technique to measure aerosol and fog concentrations and particle size distribution under SA conditions. The competence in FASP methodology was maintained by updating the post-processing tool.
- Unfortunately, limited attention was paid to measurement uncertainty in these presentations.

2.3. Session II-1: Conductivity and impedance methods (Part 1)

Session Chair: **Atsushi Ui** (Central Research Institute of Electric Power Industry, Japan)

Presented papers:

Table 2.3. Papers presented in session II-1

#005	Defining void fraction with axial wire-mesh sensor in a swirling two-phase flow ***J. Telkkä**, S. Jämsén and J. Hyvärinen*
#013	The void fraction dynamics in vertical rod bundles ***Z.-C. Li**, Q.-Y. Ren, S. Du, L.-M Pan and J. Deng*
#035	Improvement of TOPFLOW void fraction data using potential field simulations of the wire-mesh sensor response ***H.M. Prasser**, M. Beyer and D. Lucas*

Session II-1 showed novelties and progress made in conductivity and impedance methods:

- An axial wire-mesh sensor named “AXE” was developed, and the applicability to swirl flow measurement was investigated (#005).
- A method to measure void fraction dynamics in a sub-channel using 12 electrodes on a ferrule-type spacer grid was developed (#013).
- A method named “MAXWELL_NO_CUT” to correct measurement data that resulted in negative void fraction was developed (#035).

Regarding validation needs and measurement uncertainty one can note:

- New measurement techniques using wire-mesh sensors (WMS) or electrodes, and the overshoot correction method were developed. Validity of the techniques was discussed based on confirmation of their applicability by comparison with experimental data.
- Paper #035 described work in progress rather than final results concerning the quantification of accuracy and uncertainties.

The main lessons learnt in this session are:

- New measurement techniques by using WMS or electrodes were shown. There is a possibility that measurement techniques with the existing WMS or electrode could be improved and further advanced.
    - For example, "overshoot" in WMS measurement could be improved by a signal processing based on Maxwell's equation.
- In the development phase of new methods, validation data with spatial and temporal resolution equal to or better than model resolution is needed.

From this session, one can make the following recommendations for future R&D activities:

- It is expected that nonintrusive axial sensors will be developed (#005).
- It would be interesting to develop a method to identify the flow regime of two-phase flow by means of frequency analysis of the measured data regarding void fraction (#013).
- All measurement methods include pros and cons. As suggested by the author in the conclusion, it was recommended to conduct experiments with a combined use of WMSs and nonintrusive reference methods to confirm the validity of a new method. (#035)

2.4. Session II-2: Conductivity and impedance methods (Part 2)

Session Chair: **Fabio Moretti** (Nuclear and Industrial Engineering, Italy)

Presented papers:

Table 2.4. Papers presented in session II-2

#022	Experimental studies and measurement uncertainty estimations of the flow mixing in PWR pressure model
	M.A. Bolshukhin, A.V. Budnikov, D.N. Patrushev, ***A.A. Barinov****, S.M. Dmitriev and A.E. Khrobostov*
#036	Response of electrical film thickness sensors to waves in the liquid film
	H. M. Prasser
#038	Wire mesh sensor measurements of a co-current two-phase flow in a spent fuel pool-like rack
	G. Brillant *and B. Fourré*
#049	Investigation of liquid film thickness distribution in air-water experiment simulating emergency coolant bypass using electrical conductance method
	C.-J. Choi and ***H. K. Cho***

Session II-2 presented applications of the wire-mesh sensor (#022, #038) and of electrical film thickness sensors (#036, #049), and showed that there is still some interest towards the investigation of single-phase mixing, including the difficulties in correctly predicting flow rotation phenomena in the downcomer, or limitations in turbulence modelling approaches, which require further CFD-grade data.

- The session highlighted a trend to better question the quality of the measurement and to identify and try to correct the sources of errors.
    - For example, the presenter of #022 raised the question of whether certain in-vessel mixing experimental data sets (such as those from the Rossendorf Coolant Mixing Mode [ROCOM] test facility) are CFD-grade or not, providing an interesting discussion.
    - The metrics for code-to-experiment quantitative comparison could also need further discussion (but this is beyond the workshop's scope).
    - Use of math-based approaches to assess sensor response (such as in #036) was crucial to measurement uncertainty quantification (UQ). Such a rigorous attention to UQ may not be sufficiently common yet. There is still a need to focus on fundamental aspects (e.g. idealised wavy film behaviour). There may still be a long way to achieving realistic/prototypic conditions.
    - Discrepancies between averaged void fraction obtained by differential pressure measurements and by WMS were reported in #038, the interpretation of which is unclear (limitations in the sensors, raw data post-processing, or in test arrangement/procedures?). It would be interesting to investigate further.
    - Concerning WMS: the "MAXWELL_NO_CUT" correction proposed and recommended by Prasser in 2016[1], is probably not yet applied systematically.
- Some lessons learnt from this session are:
    - In general, it would probably be beneficial to enhance technical exchanges between experts and experimentalists, possibly from different research groups.
    - When phenomenological complexity increases (e.g. emergency core cooling [ECC] bypass case, with water entrainment, break-up), and code-to-experiment comparisons are attempted (as shown in #038), there seems to be still a long way to go.
    - The application of an ad hoc sensor to film thickness measurement in prototypical reactor geometry (paper #049) seems to be an innovative aspect.

1. Paper #019 "Signal Response of Wire-Mesh Sensors to an Idealised Bubbly Flow" presented by H.-M. Prasser at SWINTH in 2016.

2.5. Session III: PIV - LDA and LIF

Session Chair: **Ralf Kapulla** (Paul Scherrer Institute, Switzerland)

Presented papers:

Table 2.5. Papers presented in Session III

#002	Temperature variations around single nucleate boiling bubble measured with a miniature thermocouple
	*M. Takeyama, **T. Kunugi**, Z. Kawara and T. Yokomine*
#020	Experimental study on flow structure inside subchannels of 8×24 rod bundle arrays
	***S. Kim**, S. U. Ryu, B.-G. Jeon, H.-S. Choi and S.-K. Moon*
#032	A digital holographic measurement of a sphere-packed pipe by a refractive index-matching method
	*Y. Matsuda, A. Myoga, K. Daigo, N. Unno, K. Yuki, Y. Seki and **S.I. Satake***
#056	Dynamic measurements of the flow and structure oscillations to validate FSI calculations
	*M.A. Bolshukhin, A.V. Budnikov, **E.I. Shmelev**, D.A. Kulikov, A.V. Loginov, A.S. Suvorov, A.N. Stulenkov*

Three papers of Session III dealt with applications of laser-based techniques to various problems, such as observation of single-phase flow in a rod bundle, measurement of the flow field in a sphere-packed pipe, and dynamic measurement of flow in a fluid-structure interaction configuration. Paper #002 dealt with the use of miniature thermocouples to measure liquid temperature near an isolated nucleate bubble (so this paper had erroneously been assigned to this session).

Some discrepancies were pointed out between the material included in the manuscripts and in the presentations, which somehow affected the evaluation:

- As regards to paper #002, a large part of the presentation focused on additional material to what was included in the article. The presentation discussed the relation between liquid behaviour in the superheated sublayer and linear temperature profile in there.
- Similarly, the presentation of paper #020 entirely focused on results from the PRIUS-I test facility, whereas the article addresses PRIUS-II results (which then must have turned out to be affected by some issues).

The following elements of novelty can be highlighted:

- Paper #032 presented an interesting and original measurement technique (digital holographic method, relying on a refractive index-matching method) applied to a pebble bed-like geometrical configuration.

The following remarks were made:

- As regards paper #002, it was pointed out that a vertical movement of a 25 μm thermocouple probe by 1 μm steps may represent too much of a spatial disproportion in terms of spatial averaging around the probe compared with the probe movement. Moreover, the influence of the mechanical vibrations of such tiny probes was apparently not taken into account.

- As regards paper #032 and its related presentation, the limited amount of detailed information provided about the proposed technique leaves some unresolved issues. For example, the velocity data were obtained at the location where the particle and the corresponding holographic pattern were discovered (similar to particle tracking), but most post-processing techniques (derivatives, etc.) require a regularly spaced velocity grid. Consequently, the data need to be interpolated to this regular grid. The presented velocity fields were extremely sparse which might result in noticeable difficulties for this interpolation. Moreover, revised communication should explain how the authors considered and eventually excluded the holographic signals resulting from particles settled (and finally sticking) to the pebbles, since these particles will result in a form of pedestal, eventually distorting the intended holographic signal.
- Concerning paper #056, a "zero" experiment should have been performed without the cylinders installed, to test for the "zero" spectrum of the loop since the loop has no settling chamber installed such that (at least in principle) part of the spectrum might be equally caused, for example by the pump oscillations. Additionally, one figure showed a very large and abrupt jump (more than two orders of magnitude) in the "natural" shedding frequency of the flow behind one cylinder, which needs to be explained.

2.6. Sessions IV-1 and IV-2: Local single- and multi-sensor probes (Part 1 and 2)

Session Chairs: **Lionel Rossi** (Commissariat à l'Energie Atomique et aux Energies Alternatives, France) and **Klaus Umminger** (Framatome GmbH, Germany), respectively.

Papers included in the sessions:

Table 2.6. Papers included in sessions IV-1 and IV-2

#019 (IV-1)	Single optical fiber probe method for local droplet parameters in the horizontal stratified and annular flows
	***B. Bae**, T. Kim, J. J. Jeong, K.D. Kim and B.J. Yun*
#026 (IV-1)	Error in bubble velocity measurement using 4-sensor void probe due to interface deformation
	***A. Satou**, J. Sagawa, H.M. Sun, Y. Sibamoto and T. Yonomoto*
#040 (IV-2)	Correlations between superficial gap velocities and interfacial velocities for two-phase flows in simulated tube bundle [**NOT PRESENTED**]
	T. Nariai, R. Kawakami, Y. Komuro, A. Kodama, Y. Kondo, S. Azuma, H. Morita, Y. Nishikawa
#042 (IV-1)	Applications of sacrificial thermocouples for various severe accident experiments using high temperature of melt
	***S. M. An**, H. Y. Kim and S. W. Hong*
#054 (IV-2)	Thermal radiation effect on thermocouple measurements
	*C. Falsetti, **R. Kapulla**, S. Paranjape and D. Paladino*

Session IV-1 and IV-2 presented four very different applications of local single- and multi-sensor probes, with some novelties, some considerations on measurement accuracy/error corrections and recommendations for future research activities:

- A single optical fibre probe method was used for local droplet parameters in the horizontal stratified and annular flows (paper #019) in detailed experiments with some explanations about velocity measurements. It was argued that 100 droplets may not be enough to statically converge, as claimed by the authors.
- An analytical experiment was presented (paper #026) investigating the impact of interface deformation using multi-tip phase indicators on velocity measurement. An empirical correction was proposed for correction that was limited to low velocity (below 0.5 m/s), the error tending to decrease with increasing speed.
- Different test facilities were presented (paper #042) dealing with experiments with high temperature melt in water and "concrete". The conclusion of the presentation emphasised improvements required to enhance the accuracy of measurements. In particular, the need for shorter response times was highlighted. This need seems more important for experiments in water than for experiments in concrete as the durations of the experiments are different. Durations were noted to be about 1s (or less) for the water experiments and 100s for concrete experiments.
- A presentation was made on the thermal radiation effect on thermocouple measurements (paper #054). Despite enormous progress in the development of new measurement techniques in recent years, "conventional" instrumentation like the thermocouple-based temperature measurement still plays an important role in experimental reactor safety research. With the presented study on the thermal radiation effect on thermocouple measurements, an important and relevant subject was addressed. Interestingly, the importance of the impact of the sensor emissivity was investigated and quantitatively determined. The method, the procedure and the results of the presented study were clearly described and the uncertainties adequately addressed. The effect of thermal radiation on the thermocouple measurement could be distinctly demonstrated, whereas some additional information regarding the relation to other error sources would have been useful. As reported, the experimental results were obtained under clear, well-defined and well-known boundary conditions. It would be of interest to extrapolate the findings to "real" conditions, e.g. in large-scale test facilities and to assess/confirm corresponding compensation methods for the thermal radiation effect. This could be subject to future research activities.

Paper #040, which was meant to be part of Session IV-2, was not presented. However, it has been included in the proceedings of the workshop.

2.7. Session V: Flow visualisation methods

Session Chair: **Tomoaki Kunugi** (Zhejiang University, China)

Presented papers:

Table 2.7. Papers presented in session V

#011	Experiment study on film width and thickness of free falling water film on a large inclined plate
	***P. Hu**, X. Huang, K. Bao and G. Zhu*
#025	"Infrared vision": towards a solution of the heat partitioning controversy in boiling and CHF
	*A. Kossolapov, C. Wang, J. H. Seong, G. Su, B. Phillips, J. Buongiorno and **M. Bucci***
#039	On oxidation of a zirconium droplet falling in subcooled water
	***Q. Guo**, L. Manickam, A. Komlev, Y. Deng, W. Ma and S. Bechta*
#058	Hydrodynamic aspects of melt jet breakup in fuel-coolant interactions
	***K.-H. Bang**, H.-T. Kim and M.-S. Kim*

Session V presented various applications of optical and flow visualisation methods (such as laser confocal sensors, infrared vision, and high-speed cameras) to different phenomena and processes, such as measurement of film thickness and width (in passive containment cooling system [PCCS]-like configurations), characterisation of boiling heat transfer, investigation of the oxidation of a molten Zirconium droplet in subcooled water, and observation of the break-up of a molten metal jet into water.

The following elements can be highlighted:

- The work described in paper #011 was one of the few existing studies focusing on hydrodynamic behaviour in partially film-covered flow conditions. New correlations for film width and thickness were derived based on the outcomes of the experiment.
- The experiments presented in paper #025 provided new high-resolution data for validation of wall heat-partitioning models, focusing not only on quantities that characterise the various basic phenomena involved in boiling, but also directly on the heat flux terms.
- The experiments presented in paper #039 provided insight into oxidation processes involved in fuel-coolant interaction, and quantitative information on hydrogen production (rate and total).
- The investigation in paper #058 also contributed to some extent to the understanding of some basic phenomena featured in fuel-coolant interaction.

The following lessons learnt can be pointed out:

- As regards to the free-falling water film study, further investigations should address the sensitivity to the wall wettability (e.g. in relation to ageing issues) and to the way of feeding the water.

- Concerning the study on wall heat partitioning, measurement of near-wall liquid temperature (together with infrared [IR] measurement from the backside of the wall) should be considered, and efforts should be made to separate the transient conduction from the convective heat transfer on the wall.
- In the experiments on zirconium droplet oxidation, it was found that the O/Zr atomic ratio obtained with a scanning electron microscope (SEM) / energy dispersive X-ray spectroscopy (EDS) analysis was significantly large compared to the value obtained by stoichiometry calculation according to hydrogen production. Thus, the result by SEM/EDS could be more useful to reveal the microstructure of the debris and to indicate the influenced depth by oxidation interaction between molten zirconium and coolant instead of indicating the oxidation degree of the Zr droplet. As for high-speed video image processing, the oblate ellipsoid assumption of bubble shape leads to some deviation when the bubble deforms, and as for SEM/EDS, it gives systematic deviation of the oxygen concentration. During the discussion, it was pointed out that the solubility effect of the hydrogen bubble on the amount of collecting hydrogen should be investigated.
- In the experiment on molten jet break-up, it was found that there was an obvious difference in jet break-up behaviour between the fully-flooded and the partially-flooded cavities. Unfortunately, the melt jet temperature was lower than the boiling point of the coolant, so that only the hydrodynamic aspect of jet break-up could be investigated. It is important to understand the fundamental physics, but it is not clear how to relate this pure fluid dynamics result to the real fuel-coolant interaction (FCI) phenomena.

2.8. Session VI: Thermal anemometry and anemo-thermometry

Session Chair: **Matteo Bucci** (Massachusetts Institute of Technology, United States)

Presented papers:

Table 2.8. Papers presented in session VI

#023	Experimental study on the heat flux of a heat exchanger for passive cooling of spent fuel pools by temperature anemometry grid sensor ***S. Unger**, M. Arlit, M. Beyer and U. Hampel*
#048	Measurements of void fraction, liquid temperature and velocity under boiling two-phase flows using thermal-anemometry ***F. Francois**, H. Djeridi, S. Barre and M. Klédy*

Session VI presented new applications of anemometry and anemo-thermometry to some investigations of a passive condenser and to two-phase boiling flow.

- General comment:
  - Both papers discussed the use of thermal anemometry to make measurements of temperature and velocity. Thermal anemometry (or anemo-thermometry) is a well-established technique. Still, major challenges arise when applying this technique to two-phase flows, as discussed in paper #048.

- Some lessons learnt:
  - Thermal anemometry has been used to study the behaviour of the air-side of a passive condenser (paper #023). The sensor has been used to measure both temperature (in the low-current mode) and velocity (in the high-current mode). The technique, as implemented, allows measurements at a frequency of a few Hertz. The work presented does not deal with the development of the sensor or the measuring technique, but rather with a very meaningful application.
  - The use of thermal anemometry to perform measurements of temperature, void fraction, and velocity in two-phase flows was presented (paper #048). The authors presented measurements of non-dimensional velocity and temperature boundary layers in subcooled nucleate boiling. The presentation also addressed important open questions and challenges about how to perform accurate and reliable two-phase flow measurements. The work was sound. Although it seems to be work in progress, it shows high potential.

2.9. Session VII-1: Radiographic and tomographic methods (Part 1)

Session Chair: **David Novog** (McMaster University, Canada)

Presented papers:

Table 2.9. Papers presented in session VII-1

#001	Design of an electrical impedance tomography detector for two-phase flow measurements in the PKL (Primary Coolant Loop Test Facility) experiment
	*M. Darnajou, **C. Dang**, G. Ricciardi, S. Bourennane, C. Bellis and H. Schmidt*
#009	Improvement of high-speed neutron imaging for visualisation of reflooding phenomena
	***D. Ito**, K. Ito and Y. Saito*
#037	Time averaged tomographic measurements of flow conditions before and after dryout in a simplified boiling water reactor (BWR) subchannel geometry
	***L. Robers**, C. Bolesch, R. Adams and H.M. Prasser*

Session VII-1 featured various tomographic techniques (electrical impedance tomography, high-speed neutron imaging, X-ray tomography) to investigate two-phase flow phenomena.

The following elements of novelty can be highlighted:

- In the study presented in paper #001, a technique was developed that can be applied to investigate the two-phase flow in relatively large pipes. Numerical modelling of electromagnetic fields was used to optimise the sensor performance by minimising the energy leakage. An innovative data acquisition system was developed on purpose.
- Paper #009 presented efforts made to perform very fast neutron radiography (with frame rates as high as 10 000 fps) to observe reflooding phenomena, using Kyoto University Research Reactor beamline.
- The work in paper #037 approached two-phase flow phenomena in prototypical BWR sub-channel geometries, for which there seems to be a lack of high-resolution experimental data suitable for code validation.

The following lessons learnt can be pointed out:

- The proposed measurement system was tested by placing cylindrical sticks inside the sensor and observing reconstructed images. The use of more representative shapes and trajectories might be useful in further demonstrations. Moreover, it would be interesting to see the transducer applied in large-scale integral test facilities (ITFs) as there was a lack of such data for system code validation.
- Concerning the work on high-speed neutron tomography, interesting work was conducted to address noise in the images. One might question the actual need for 10 000 fps vs. 500 fps, with some images averaging to reduce random noise. Additionally, it is suggested that the neutron images be couple with wall temperature measurements (by IR camera), so that rewet temperature evolution can be observed.
- While the mixing vane design was not representative of real BWR, there was clear measurement of the changes in liquid film around the vanes and downstream. There was evidence of a "critical" liquid film thickness (i.e. even cases far from dryout show film thickness similar to cases which are much closer to dryout).

2.10. Session VII-2: Radiographic and Tomographic methods (Part 2)

Session Chair: **Horst-Michael Prasser** (ETH Zürich, Switzerland)

Presented papers:

Table 2.10. Papers presented in session VII-2

#004	Spectral and eigenvalues analysis of electrical impedance tomography data for flow regime identification
	***C. Dang**, M. Darnajou, G. Ricciardi, L. Rossi, S. Bourennane, C. Bellis and H. Schmidt*
#055	Preliminary results on the development of a fast-neutron tomography system for phase distribution measurements
	*G. G. Patterson, and **D.R. Novog***

Session VII-2 was about radiographic and tomographic methods.

Some novelties were presented:

- A fast electrical impedance tomography (EIT) system (paper #004) for gas-liquid flows in a horizontal duct was presented with design corresponding mainly to the current state-of-art in the field. The sensor was in a state of applicability for tabletop testing with phantoms. The performance of different iterative image reconstruction methods was demonstrated using a cylindrical phantom. The merits of EIT lie mainly in the low costs and the fast time response of these techniques, whereas the spatial resolution and the fidelity of the imaging have clear limitations. The main innovative element of the presentation consisted in the discussion of pattern recognition methods based on an evaluation of power density spectra and an eigenvalue decomposition of the primary measuring data. The approach was an interesting alternative to a full tomographic reconstruction in case of primary data stemming from physical fields with a strong non-linear transfer behaviour and ill-posed inverse tasks, causing a low fidelity of the reconstructed distributions. It can

be generally remarked that such an approach can also provide useful additional information when applied to other types of tomographic imaging. During the Q&A, resolution limitations typical for EIT were tackled. It was proposed to use spherical phantoms of different diameter representing gas bubbles better than cylinders arranged parallel to the axis. It was reported by the presenter that such tests were performed with the result that the contrast was much lower but the object could still be detected as such.

- A tomography system (paper #055) based on the attenuation of fast neutrons generated by a commercial deuterium-deuterium plasma fusion generator providing a projected output of 2e8 to 1e9 neutrons per second in 4π of neutrons at an energy of about 2.5 MeV was presented. Proton recoil conversion and plastic scintillators coupled to semiconductor photomultipliers were used as detectors. The planned application consists in void measurements in CANDU (Canada Deuterium Uranium [Canadian-type pressure tube heavy water reactor]) bundles. Monte Carlo calculations were used to predict and optimise the imaging performance. The achievable resolution makes it possible to detect thin liquid films on fuel rods. The overall void fraction distribution can be obtained as a time-averaged field. Measuring time is expected to be in the range of tens of minutes. The facility itself is still under construction. In case of success, the facility can provide new understanding of the object of interest, which is a considerable achievement in view of the contrast problems that persist in imaging small-scale and low attenuating objects housed in heavy metallic structures.
- The discussion addressed the question of correcting for deformations of the fuel rod bundle between measurement and calibration regimes due to thermal expansion and pinch effects, as well as the expected efficiency of the fast neutron detectors.

2.11. Session VIII: Pressure-based measurements

Session Chair: **Sevostian Bechta** (KTH Royal Institute of Technology, Sweden)

Presented papers:

Table 2.11. Papers presented in session VIII

#010	Unsteady pressure measurements in 5x5 rods bundle using single and multi-sensors devices *N. Turankok, F. Bazin, V. Biscay, T. Lohez, F. Moreno, S. Testanière and **L. Rossi***
#012	Measurement of corium surface tension using the maximum bubble pressure ***N. Chikhi**, J. Delacroix, P. Fouquart and B. Turquais*

The two papers presented at session VIII dealt with the use of pressure-based measurement techniques for diverse purposes, such as investigation of pressure fluctuations in fuel bundle flows (with and without mixing vanes) and measurement of surface tension of corium melt.

The following elements of novelty can be highlighted:

- By addressing the problem of fuel rod vibrations and wearing, paper #010 quantified the pressure and velocity fluctuations at different locations around the central instrumented rod of the test bundle with cold water flow having characteristic velocity of 2.4 m/s, in particular, with a focus on the effect of spacer grids with and without mixing vanes. Dynamic local pressures and velocities were measured by one and eight compact pressure transducers located in the single- and multi-sensor versions of the test bundle, and by means of LDV (Laser Doppler Velocimetry) with 4μm NYLON spherical particles in the water. The distribution of pressures around the rod was measured by turning the instrumented rod having radial pressure measurement channels with increments of 10° over 360°. The novel local pressure measurements, in combination with the central instrumented rod rotation and LDV measurements, enabled valuable results on azimuthal and vertical distributions of flow parameters, as well as quantification of the mixing vane effect on the flow homogenisation. These were presented and discussed. Accumulated experimental data can be used for comparison with model predictions and CFD results.
- Paper #012 presented new results on measurements of liquid corium properties, which are generally poorly known, thus contributing to the advanced modelling of SA progression in different light water reactors. The authors studied the melt surface tension of chemically prototypic corium at very high temperatures creating many experimental and measurement problems, which are quite effectively solved with the use of maximum bubble pressure (MBP) technique previously approbated and used in RASPLAV[2] and MASCA (material scaling) NEA projects. The surface tension measurements were supported by detailed material study and characterisation of specific corium compositions. Measurement uncertainties and calibrations were addressed and discussed carefully in the paper. This created good perspectives for the continuation of the study in order to cover a wide range of corium compositions and temperatures, which is of interest for SA research and safety analyses. Research perspectives for corium properties were also presented.

The following lessons learnt can be pointed out:

- The discussion of the presented paper #010 focused on possible facility effects on the measured pressure oscillations/frequencies and research connections with the present papers about CFD-grade experiments. Further experiments with the multi-sensor measurements can be recommended for possibly more prototypic conditions in respect to reactor bundle.
- The presentation of paper #012 initiated a useful discussion about temperature measurement uncertainty at very high temperatures when using multi-wavelength pyrometers, a sudden drop of capillary pressure during MBP measurements and research perspectives in general.

2. The Russian word for melt.

3. Further outcomes of summary session and open discussion

This section is based on the organisers' and Chair's notes and impressions from the workshop, especially the closing session.

3.1. Scope

According to a large majority of participants, it is appropriate to have both TH and SA areas covered in the same WS, without parallel sessions. The mix between the two areas was appreciated also because in some cases (e.g. containment experiments) it is difficult to make a sharp separation between them. In general, it is interesting for specialists from one community to have a close look at the work of another community.

There has been a certain imbalance between the number of papers pertaining to the two domains (28 TH and 8 SA). A larger number of SA-related papers in a future workshop would be desirable, in order to obtain a more accurate view of current experimental efforts and technological challenges in this domain.

Furthermore, the following suggestions were made:

- Extend the work to molten salt reactors, liquid metal cooled reactors, Generation IV in general and any new reactor design.
- Extend work to non-nuclear domains (oil and gas, chemical process industry, etc.), provided that elements of common interest with the nuclear community can be shown.

However, it has to be noted that the scope of the SILENCE Network is limited to light water reactors (LWR).

It is worth mentioning that, outside the nuclear context, there are expert communities focusing on specific technologies (e.g. PIV user groups) that might be interesting to look at. It could be possible to involve these experts in future SWINTH workshops.

3.2. Technical-scientific contents

According to a questionnaire on the quality of the workshop, the attendees generally appreciated the quality of the papers and presentations in the technical sessions, as well as the invited lectures. The workshop was found to be inspirational for new developments.

As far as existing techniques are concerned, some improvements were shown, some shortcomings were pointed out and attempts to identify sources of errors were made (although much work remains to be done and emphasis needs to be given to measurement uncertainty quantification). Some innovative ideas were also presented.

It was stressed, during the summary open discussion, that the WS focus should not be limited to instrumentation-related issues; rather, it should also address the target utilisation of experimental data (e.g. for code validation purposes), and the instrumentation needs that

are highlighted therein. Invited lectures and/or dedicated panel sessions addressing this aspect should be considered. On the other hand, the requirement that the papers focus on experiments, measurement techniques and instrumentation should be kept, and no session specifically devoted to experimental data utilisation should be envisaged.

Several participants shared the idea that more time should be left to discussions and brainstorming, focusing especially on open issues and new concepts rather than on the successful application of existing technologies. There could be some time for discussion at the end of each session, as well as additional panel sessions.

There should also be a focus on topics related to nuclear power plant application (both current and potential). A stronger involvement of utilities would be appropriate for such a purpose, e.g. through an invited lecture.

The following topics were suggested for possible invited lectures for the next SWINTH:

- Use of experimental data for code/model development and validation.
- Reactor instrumentation needs (e.g. from utilities).
- Measurement uncertainty (e.g. from GUM framework).
- Big data analysis and machine learning methods for enhanced exploitation of experimental data.

It was suggested to introduce the following in the panel sessions and discussions:

- A panel session on measurement uncertainty, with short presentations given by a few specialists to initiate an open discussion.
- A panel session on needs related to code/model validation, with short presentations given by a few specialists to initiate an open discussion.
- A brainstorming parallel session between small groups of specialists about fully innovative techniques (to be then reported about during the workshop).

It is worth noting, however, that there are inherent limitations in “brainstorming” sessions in the context of such a workshop, since intellectual property-related issues may prevent the involved experts from sharing new ideas.

3.3. Paper review process

- A few participants suggested simplifying, or even avoiding, the peer-review process of submitted abstracts and papers. The advantages would be to substantially reduce the burden on all those who are involved in the WS organisation, in writing the papers and in the review process itself, and to restructure the time schedule (so that papers do not need to be submitted so far in advance). The focus would then be on the WS itself and on the discussions and technical-scientific exchanges.
- However, according to the organisers and the majority of participants, such a substantial revision of the WS format would not be compatible with the general objectives of the SWINTH workshops (as intended so far) and with the requirements of WGAMA events, and would probably bring a decrease in the overall quality of the selection and of the WS itself (for which good discussions may not be enough).

- The well-organised peer-review process is regarded as a guarantee of quality also in the European Commission framework.
- Moreover, the paper review process is also an opportunity to instil the importance of this approach in young researchers.
- Some participants suggested the following alternate paper review process: the authors upload their papers on a web platform; then, any "users" logged into the platform can view the papers, upload their comments and interact with the authors. However, it was pointed out that such an approach is prone to several problems, including copyright issues. After some discussion, the idea was dropped.

3.4. Measurement uncertainty

- There still is a lack of a systematic and thorough approach to measurement uncertainty in much of the presented experimental work. On the other hand, there seems to be a tendency in the community to spend increasing effort on this important issue. For instance, more papers in SWINTH-2019 included uncertainty-related information than in SWINTH-2016 (as encouraged by the SWINTH-2019 Announcement).
- Uncertainty quantification may require huge additional efforts for measurements, as it does for code predictions. The SWINTH-2019 call for abstracts and call for papers incited the authors to address the uncertainty. However, not addressing the measurement uncertainty was not deemed a sufficient reason to reject papers which reported novel techniques or advancements in existing technology.
- It was observed that guidelines on measurement uncertainty do exist (such as the ISO "GUM", Guide to the Expression of Uncertainty in Measurement, developed by the Joint Committee for Guides in Metrology), but they are often not referenced, so the question arises whether those guidelines are actually used or not. An invited lecture on this topic at the next SWINTH may be appropriate (as mentioned above), in order to obtain an idea of the applicability to nuclear reactor thermal hydraulics-related experiments.
- Some participants stressed the fact that the focus should be put on how to deal with measurement uncertainty rather than on how to passively use the uncertainty data provided by instrument developers and vendors.
- There were suggestions to draft a handbook providing a state of the art and guidelines on measurement techniques, possibly based also on the WS outcomes. Such tasks would require the involvement of a reasonably large number of experts and the allocation of considerable resources, so undertaking it in the present organisational framework would be hard, perhaps even impossible. However, it is interesting to point out the existence of such a need for guidance, which might be worth addressing in the future in appropriate frameworks.

3.5. WS format and structure

- The size of the WS, with about 65 participants overall, 5 invited lecturers and 36 papers presented orally (25 minutes each, including Q&A), was found suitable to allow for good exchanges and interactions.
- The short session devoted to sponsors was generally appreciated. Some sponsors' presentations stimulated questions and discussions.
- The length of the WS (3.5 days) was generally found to be acceptable. However, there was a general preference for a shorter duration (e.g. 3 days) and a clear preference to avoid a longer duration.
- The choice to avoid parallel sessions turned out to be appropriate for most people.
- Poster sessions should be considered as an option for the next SWINTH, as they would make it possible to reduce the WS length.
- Most of the participants supported the idea of holding the next SWINTH after three years.

4. Outcomes of quality survey

A questionnaire (shown in Figure 4.1) was delivered to all workshop participants to collect their feedback about the quality of the workshop material and organisation.

Figure 4.1. Questionnaire for quality survey

Questionnaire for Participants

Quality survey [*1=Poor; 2=Fair; 3=Good; 4=Very good; 5=Excellent***]:**

Item	Rate	Reason
Overall scientific level of the workshop		
General quality of papers		
General quality of presentations		
General quality of keynote lectures		
General quality and interest of discussion sessions		
Interest of combining TH- and SA-related experimental areas into a single workshop		
Workshop structure		
Size of the workshop (no. of presentations)		
Avoiding parallel sessions (at the cost of a longer WS duration)		
Organization and logistics		

Further questions:

Anything missing/lacking?	
Anything you would change?	
Should there be another SWINTH in the future? If Yes, in how many years?	
Is the scope OK? Would you extend it to other topics (and which ones)? Or would you reduce it (by cutting which topics)?	
Any other criticisms, suggestions, recommendations, proposals for the future	

Only 15 completed questionnaires were returned to the organisers, so an accurate statistical analysis cannot be made. Nevertheless, the outcomes of the survey are summarised and presented below, as they can still provide useful input for the evaluation of the SWINTH-2019 and for the preparation of the next SWINTH workshop.

Q1 - Overall scientific level of the WS

In general, participants gave positive feedback about the scientific level of the WS. Some participants highlighted its dedication to the experimental techniques and the number of novelties presented. One participant stated that the WS was held too close to the previous one. Another said that not so many innovations were presented. One participant stated that a few presentations were out of scope. It should be noted that the same participant suggested modifying the scope of the WS to further reduce the talks dealing with the use of experimental data, focusing more on measurement technique issues.

Q2 - General quality of the papers

The general quality of the papers was rated, on average, as very good. Four participants did not answer this question. One participant lamented there was too little time available to read the papers (note: all the papers were made available for download during the workshop).

Q3 - General quality of the presentations

The general quality of the presentations was rated, on average, as very good. One participant did not answer this question. One participant stated that some speakers did not provide enough details about measurement techniques during their talks. One participant observed the low quality of the figures in some of the presentations (it should be noted that the lack of a good audio/video system in the room, as lamented by four participants, may also have influenced the rating of the presentation quality).

Q4 - General quality of the KN lectures

The general quality of the keynote (KN) lectures was on average rated as very good. One participant observed that no KN lectures were specifically devoted to SA. Two participants stated that some of the talks were not interesting or relevant enough as KN lectures or that too few innovations were presented. One participant observed that some KN lecturers did not stimulate debates.

Q5 - General quality and interest of discussion sessions

The general quality and interest of discussion sessions was on average rated as very good. One participant did not answer this question. One participant reported difficulties in following the discussions (in English). One participant suggested that some time should be allocated for open discussion at the end of each session (it should be noted that the lack of a good audio/video system in the room, as lamented by four participants, may have influenced the rating of the presentations quality).

Q6 - Interest of combining TH- and SA-related experimental areas into a single WS

Almost all the participants expressed very positive feedback on the combination of TH- and SA- related experimental areas into a single WS. One participant stated that this should be avoided.

Q7 - WS structure

The WS structure was on average rated as very good. One participant suggested having a longer break at lunch time. Another participant suggested distributing hard copies of the papers at the meeting.

Q8 - Size of the WS (number of presentations)

The size of the WS was on average rated as very good. One participant observed that having a larger attendance may be beneficial. According to one participant, the WS could be slightly shorter.

Q9 - Avoiding parallel sessions (at cost of a longer WS duration)

Avoiding parallel sessions was highly appreciated by most participants. One participant suggested organising separate SA- and TH-related sessions. One participant answered that the duration of the WS is appropriate although the meeting should finish earlier every day (e.g. 5 PM). One participant gave a low rate without providing an explanation.

Q10 - Organisation and logistics

Organisation and logistics were on average rated as very good. One participant did not answer this question. One participant complained about the audio/video system. One participant expressed interest in the organisation of technical tours. One participant observed the lack of a shuttle service to\from the banquet venue (note: about 2 km walking distance from the workshop venue). One participant gave a low rate (2/5) because they did not receive a paper acceptance notification. The same participant suggested distributing printed proceedings, putting tables showing the programme and related information in the conference room, selecting a more convenient location, organising a business card exchange session and increasing "journal transfer".

Summary of "further questions"

Additional feedback from participants is reported hereafter:

- Some participants mentioned the low quality of the audio/video system in different parts of the questionnaire.
- Possibility of avoiding abstract submission in advance to have more participants. It should be noticed that the same participant expressed an average rate (3/5) about the general quality of the papers.
- Participant papers from utilities and industries were missing.
- To consider organising a "best paper awards" to motivate people.
- To give a presentation on the general NEA policy.
- To improve the payment system (some failures experienced using credit cards).
- To receive the WS material, including papers, 1-2 weeks in advance to facilitate discussions.
- To consider organising the WS in a different location (e.g. different city, university premises).
- To consider issuing a handbook about measurement techniques. The handbook may consist of a review of all the available techniques useful for TH investigations.

- To reduce the number of presentations and increase the time available for questions and answers.
- To consider the "gender issue" by also inviting women among keynote lecturers.
- To organise a keynote lecture inviting PIV experts from AIVELA (Italian Association of Laser Velocimetry) or AFVL (French-speaking Association of Laser Velocimetry) networks.
- To collaborate with non-nuclear communities.
- One participant expressed concern about the usefulness of considering so many air-water experiments in the framework of SILENCE and WGAMA activities. An air-water experiment should be acceptable, if it is clearly stated that this is a preliminary experiment, or it has been performed because a steam-water experiment was not possible. It should also be made clear that air-water experiments should be interpreted to full scale.
- Next workshop: preferably in three years. Shorter times should not be considered since new work might not yet be ready to present.

The outcomes of the quality survey are generally consistent with those of the summary session of the workshop and with the impressions gathered by the organisers. The participants' feedback obviously is not unanimous or homogeneous, as it may be based on different evaluation criteria. Therefore, such feedback has been considered critically in the following synthesis and evaluation.

5. Recommendations and conclusions

This second SWINTH workshop attracted a high-quality community of experimentalists in thermal hydraulics related to DBA and severe accident analyses. The attendees appreciated the good level of the invited papers, the technical sessions and discussions. Some of the papers were selected for journal publication.

Eight papers – out of the total 36 presented – pertained to SA-related experimental work. The following topics were covered: investigation of fuel-coolant interaction (three papers), characterisation and removal of aerosols (two papers), characterisation of molten material and core debris properties (two papers), heat transfer processes involved in molten core cooling (one paper). Some papers dealt with consolidated state-of-the-art technology; others focused on advancements. To obtain a more exhaustive picture of the current experimental efforts and technological challenges in this vast research area it would be desirable to attract a larger number of SA-related contributions for a possible future SWINTH workshop.

Syntheses of the technical sessions were reported by the respective chairpersons. The following trends were noted:

- Novelties and progress were presented for many instrumentation techniques.
- Special efforts were made in the analysis of sources of measurement errors, as well as the quantification of accuracy and uncertainties.
- Some lessons learnt during the workshop could serve as the basis for updating the state of the art with formulations of the resulting recommendations.

Among the novelties and progress made in measurement techniques, the following can be pointed out:

- Synchronised infrared thermography and liquid film thickness sensors can provide detailed information on the film dynamics in heated annular flow.
- Combining optical fibre, high-speed camera and optical double-sensor probes can provide a better characterisation of two-phase convective boiling flow.
- Measurements of void fraction, liquid temperature and velocity under boiling two-phase flows were performed by thermal anemometry.
- A novel heat flux sensor with short response times was presented.
- An innovative technique can measure the concentration of metal elements into solutions.
- A method can measure void fraction dynamics in a sub-channel surrounded by 12 electrodes.
- An original technique in a pebble-bed-like geometrical configuration with a digital holographic method and using the refractive index-matching method was presented.

- A single optical fibre probe method was used for local droplet parameters in the horizontal stratified and annular flows.
- The design of an electrical impedance tomography detector for two-phase flow measurements in relatively large pipes is in progress.
- Fuel rod vibrations were investigated using several pressure transducers located in the bundle, and by means of LDV (Laser Doppler Velocimetry), providing valuable results on azimuthal and vertical distributions of flow parameters.
- New liquid corium properties – which are poorly known - could be obtained by measuring melt surface tension of chemically prototypic corium at very high temperatures.

Below are examples of new applications of existing techniques:

- Application of a wire-mesh sensor to swirl flow measurement.
- Wire-mesh sensor measurements of a co-current two-phase flow in a spent fuel pool-like rack.
- Investigation of liquid film thickness distribution in air-water experiment simulating emergency coolant bypass using electrical conductance method.
- Use of temperature anemometry grid sensor for a heat exchanger in passive cooling of spent fuel pools.
- Improved high-speed neutron imaging for visualisation of reflooding phenomena.
- Time-averaged tomographic measurements of flow conditions before and after dryout in a simplified BWR sub-channel geometry.
- Development of a tomography based on the attenuation of fast neutrons planned for void measurements in CANDU bundles.

Below are examples of efforts made to quantify measurement errors and uncertainties:

- Overshoot correction method developed for WMS or electrodes.
- Use of math-based approaches for the assessment of electrical film thickness sensor response to waves in the liquid film;
- Accounting for thermal radiation effects on thermocouple measurements.

A general recommendation is to continue efforts in measurement uncertainty quantification by using existing guidelines (such as the ISO “GUM”), and even by providing a state of the art and developing guidelines on specific measurement techniques devoted to nuclear reactor thermal hydraulics and severe accident analysis.

The current format of the WS, with 3.5 days, with about 65 participants overall, 5 invited lectures and 36 papers presented orally (25 minutes each, including Q&A), with short sessions devoted to sponsors, without parallel sessions, was found suitable for exchanges and interactions.

Most of the participants support having the next SWINTH three years later. The following suggestions, to be considered for the organisation of the next SWINTH, were collected:

- If necessary, poster sessions should be considered.
- Have an invited lecture on the use of experimental data for code/model development and validation.
- Have an invited lecture on nuclear reactor instrumentation needs (e.g. from Utilities).
- Have an invited lecture on measurement uncertainty (e.g. from GUM framework).
- Have an invited lecture on big data analysis and machine learning methods for enhanced exploitation of experimental data.
- More work is to be done on measurement uncertainty quantification and a panel session on measurement uncertainty could be organised, with short presentations by a few specialists to initiate an open discussion.
- A panel session on needs related to code/model validation, with short presentations by a few specialists could initiate an open discussion.
- A brainstorming parallel session among small groups of specialists about fully innovative techniques could be held.
- A large majority of participants appreciated having both TH and SA areas covered in the same WS, without parallel sessions.