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Proceedings of the Workshop on Source Term: A Report by the Committee on the Safety of Nuclear Installations Working Group on the Analysis and Management of Accidents

21-22 January 2019
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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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NUCLEAR ENERGY AGENCY

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) is responsible for the Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

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

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Executive summary

The investigation conducted in the last 15 years on different aspects of Source Term worldwide, and particularly in the context of the Nuclear Energy Agency (NEA) in the form of projects and the Working Group on the Analysis and Management of Accidents (WGAMA) activities, has resulted in a significant enlargement of the available database and an enhancement of the modelling capabilities. Nonetheless, the Committee on the Safety of Nuclear Installations (CSNI) WGAMA group considered it timely to assess the status on the matter by holding a workshop with a twofold purpose:

- to identify the knowledge gaps and remaining uncertainties in the Source Term area that might have a sizeable impact on safety; and
- to discuss the best way to address them with existing and/or future methods, analytical tools, and facilities, if needed.

The scope of the international Workshop on Source Term, held on 21 and 22 January 2019 at the NEA headquarters in Boulogne-Billancourt (France), was limited to water cooled reactors and established types of fuels. The participants expect the major outcomes of the workshop to contribute to the development of the necessary activities to address the remaining safety-significant gaps in Source Term (ST).

Generally speaking, a reasonable consensus was reached on “still open issues” worth investigating. The participants highlighted four open issues that in previous investigations had been hardly addressed or not at all:

1. Remobilisation phenomena (delayed releases); late events, either natural or caused by the accident management action, might result in the remobilisation of some fission products deposited in previous phases of the accident with the possibility of an unexpected increase in the ST.
2. Fine particles (sources, behaviour and mitigation); the potential capability of microscopic particles to remain airborne, interact with iodine, affect safety systems (and vice versa) as well as the lower efficiency of filtration systems to trap them, suggests further experimental investigations should be conducted after reviewing the current knowledge and data available.
3. Organic iodides (completion of the existing database); there is evidence that the current modelling of organic iodides is incomplete, despite the substantial improvements made in recent years, to match observations from the PHEBUS-FP tests. This being said, there is not complete agreement among iodine experts on the phenomena to investigate.
4. Fission product leaching (from the accident to decommissioning). After the Fukushima Daiichi nuclear power plant accident, a strong focus has been on the so-called long-term releases that strongly depend on the core degradation phenomena and then on the fuel leaching. These issues would need at least a review of existing models to assess the present predictive capability.

It should be emphasised that, even if some new experimental projects are to be launched in the short run, actions should be put in place to further and better exploit the data available, with the intention of maximising their usefulness for plant applications. In addition, any experimental programme should pay due attention to aspects like the representativeness of data for realistic conditions and reactor-scale conditions.

The open issues mentioned above are not a comprehensive list. There are some others presently under investigation, like high temperature chemistry and pool scrubbing. Also, the potential ST that might come from accident-tolerant fuels (ATFs), particularly, those of first generation (evolutionary type), should be given some attention. Finally, it was agreed that the leak paths during severe accidents should be in the ST research agenda.

It is foreseen that Best Estimate Plus Uncertainties methods, applied to severe accident scenarios, particularly if ST variables are adopted as Figures of Merit, will bring essential insight concerning the most necessary research in the mid-term. High expectations are placed on the H2020 Management and Uncertainties in Severe Accidents (MUSA) project and the International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) on Advancing the State-of-Practice in Uncertainty and Sensitivity Methodologies for Severe Accident Analysis in Water Cooled Reactors. In fact, a good initiative would be to ensure a close link between these projects and WGAMA during the coming years.

List of abbreviations and acronyms

AC2	ATHLET, ATHLET-CD and COCOSYS (severe accident code)
ARC-F	Analysis of Information from Reactor Buildings and Containment Vessels of Fukushima Daiichi Nuclear Power Station project (NEA)
ARTIST	Aerosol Trapping In Steam GeneraTor facility and project (PSI, Switzerland)
ASTEC	Accident Source Term Evaluation Code (severe accident code)
ATF	Accident-tolerant fuel
BDBA	Beyond Design Basis Accident
BIP	Behaviour of Iodine Project (NEA)
BSAF	Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant project (NEA)
BT	Becker Technologies (Germany)
CEA	French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives)
CHIP	Experimental facility to investigate chemistry of iodine in the reactor coolant system (IRSN, France)
CIEMAT	Centre for Energy, Environment and Technology (Spain)
CNL	Canadian Nuclear Laboratories (Canada)
CNSC	Canadian Nuclear Safety Commission (Canada)
CRP	Coordinated Research Project (IAEA)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
EC	European Commission
EPICUR	Experimental facility to investigate iodine chemistry under radiation (IRSN, France)
EURSAFE	European expert network for the reduction of uncertainties in severe accident safety issues (European Commission)
FASTNET	FAST Nuclear Emergency Tools project (European Commission)
FASTRUN	Fast-running Software Tools Used to Model Releases During Nuclear Accidents (benchmark) (NEA)
FOM	Figures of Merit
FP	Fission product

FPT	Fission product test
GRS	Gesellschaft fuer Anlagen und Reaktorsicherheit (Germany)
IAEA	International Atomic Energy Agency
IRSN	Institute for Radiological Protection and Nuclear Safety (Institut de Radioprotection et de Sûreté Nucléaire, France)
ISP	International Standard Problem
ISTP	International Source Term Programme (CEA, IRSN, France)
JAEA	Japan Atomic Energy Agency
LOCA	Loss-of-coolant accident
LTMNPP	Long Term Management of Actions for a Severe Accident in a Nuclear Power Plant
MAAP	Modular Accident Analysis Program (severe accident code)
MELCOR	Severe accident code (SNL, United States)
MOX	Mixed oxide
MUSA	Management and Uncertainties in Severe Accidents project (European Commission)
NEA	Nuclear Energy Agency
NGNP	New Generation of Nuclear Power
NRC	Nuclear Regulatory Commission (United States)
IPRESCA	Integration of Pool scrubbing Research to Enhance Source-term Calculations project (NUGENIA)
OECD	Organisation for Economic Co-operation and Development
OrgI	Organic iodides
PAR	Passive autocatalytic recombiners
PASSAM	Passive and Active Systems on Severe Accident Source Term Mitigation project (European Commission)
PIRT	Phenomena Identification and Ranking Table
PreADES	Preparatory Study on Analysis of Fuel Debris project (NEA)
RCB	Reactor containment building
RCS	Reactor coolant system
RCV	Reactor containment vessel
SAMG	Severe Accident Management Guidelines
SARNET	European Severe Accident Research NETwork of excellence
SBO	Station Black-Out
SGTR	Steam generator tube rupture
SNL	Sandia National Laboratories (United States)

SOAR	State-of-the-Art Report
ST	Source Term
STEM	Source Term Evaluation and Mitigation project (NEA)
TCOFF	Thermodynamic Characterisation of Fuel Debris and Fission Products Based on Scenario Analysis of Severe Accident Progression at Fukushima Daiichi Nuclear Power Station project (NEA)
THAI	Thermal-hydraulics, Hydrogen, Aerosols, Iodine facility and project (Becker Technologies, Germany)
UaSA	Uncertainty and Sensitivity Analysis
UQ	Uncertainty Quantification
VERCORS	A testing facility to investigate fission products release from nuclear fuels in an accident (CEA, France)
VERDON	A testing facility to investigate fission products release from nuclear fuels in an accident, follow-up of VERCORS (CEA, France)
VTT	VTT Technical Research Centre of Finland (Teknologian Tutkimuskeskus VTT Oy)
WGAMA	Working Group on Analysis and Management of Accidents (NEA)
WGIAGE	Working Group on Integrity and Ageing of Components and Structures (NEA)

1. Introduction

In the last 15 years, a good number of international projects have been carried out on Source Term, both under the auspices of the Nuclear Energy Agency (NEA) Committee on the Nuclear Safety of Nuclear Installations (CSNI) and beyond. As for the CSNI, in the last years, the Behaviour of Iodine Project (BIP), the Source Term Evaluation and Mitigation (STEM) and Thermal-hydraulics, Hydrogen, Aerosols, and Iodine (THAI) projects have provided important data on key aspects of Source Term, like iodine and ruthenium behaviour in containment in both the short and long term, including revolatilisation from surfaces and pools or even the effect of mitigation systems (passive autocatalytic recombiners [PARs], etc.). In addition, there have been a number of projects, like the Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF) project and the more recent Thermodynamic Characterisation of Fuel Debris and Fission Products Based on Scenario Analysis of Severe Accident Progression at Fukushima Daiichi Nuclear Power Station (TCOFF), Preparatory Study on Analysis of Fuel Debris (PreADES) and Analysis of Information from Reactor Buildings and Containment Vessels of Fukushima Daiichi Nuclear Power Station (ARC-F) projects, which have been set up in the wake of the Fukushima Daiichi accident and are closely related to Source Term. No less important, activities like those addressed within the NEA Working Group on Analysis and Management of Accidents (WGAMA) group on Long Term Management of Actions for a Severe Accident in a Nuclear Power Plant (LTMNPP) and the FASTRUN (Fast-running Software Tools Used to Model Releases During Nuclear Accidents [benchmark], NEA) exercise have provided and are providing elements for discussion in the area of Source Term. It is worth emphasising that in Spring 2015 an international workshop on iodine was organised by WGAMA and yielded a set of recommendations, partially addressed in the recently completed or in completion phase projects.

Beyond the CSNI, the European Severe Accident Research NETwork of excellence (SARNET) framework provided good progress on Source Term and framed a good number of small and mid-scale experimental projects on the release and transport of fission products. No less important, interpretation work of the key PHEBUS-FP experiments was also conducted under the SARNET sponsorship. The so-called PHEBUS FPT3 benchmark is worth mentioning, as it has been the last integral code benchmark with broad participation and with the main focus on fission products and aerosols release and transport. Other experiments also provided meaningful achievements in different aspects of Source Term, including mitigation, like the ones performed in:

- VERCORS (facility to investigate fission products release from nuclear fuels in an accident);
- EPICUR (facility to investigate iodine chemistry under radiation), VERDON (facility to investigate fission products release from nuclear fuels in an accident, follow-up of VERCORS) and CHIP (facility to investigate chemistry of iodine in the reactor coolant system) testing, as part of the International Source Term Programme (ISTP).

and projects, such as:

- the Aerosol Trapping In Steam GeneraTor (ARTIST) project;
- the Passive and Active Systems on Severe Accident Source Term Mitigation (PASSAM) project, etc.

With the completion of such significant work and enlargement of the knowledge base, it was timely to assess the current status and knowledge base for strengths and weaknesses and, importantly, to establish the major gaps that should be investigated in the short- to medium-term. Accordingly, the CSNI/WGAMA working group organised a workshop with two main purposes:

- to identify the knowledge gaps and remaining uncertainties in the Source Term area that might have a sizeable impact on safety;
- to discuss the best way to address them with the existing and/or future methods, analytical tools, and facilities, if needed.

The Workshop was devised to provide insights into how to proceed with Source Term research to effectively reduce primary uncertainties. All the possible inputs were considered, from OECD-related projects and WGAMA activities to past and/or ongoing SARNET (NUGENIA) and H2020 (FAST Nuclear Emergency Tools project [FASTNET]) projects. The scope was limited to water cooled reactors and established types of fuels.

The international Workshop on Source Term was held on 21-22 January 2019 at the NEA. The outcomes will contribute to enhancing the prevention and/or mitigation of severe accident consequences.

The workshop was structured in three sessions. The first session summarised the main messages from the key pillars in the Source Term domain. The second session gathered the major progress achieved and the main insights gained recently in Source Term through experimentation, model development, and from the Fukushima Daiichi accident. The third session, which was based on the two previous ones, was an open and broad discussion of the current status, the most important needs and the work ahead in the short- and mid-term. The presentations were solicited by the Organising Committee from reputed organisations in the field.

This report is a brief summary of the discussions with emphasis on the recommendations given regarding Source Term research: experimental needs and analytical work to be performed (development, validation and benchmarking).

2. Bases for discussion

This section synthesises the main issues presented and discussed in each of the sessions. It is not intended to compile every detail in each presentation, but to focus on the main points addressed and to contribute to the final discussion.

2.1. Session 1: Key Source Term background (Chaired by: Y. Maruyama, JAEA)

The introductory session consisted of three presentations:

- "Recent key milestones (and findings): from PHEBUS-FP to present times";
- "Last decade priorities: the SOAR perspectives";
- "Use of PIRT in the assessment of Source Term (ST) phenomena".

R. Lee (United States Nuclear Regulatory Commission [NRC]) presented "Recent key milestones (and findings): from PHEBUS-FP to present times". He explained the motivation for NRC to get involved in Source Term research, from the major effort launched after the Three Mile Island accident to the present times. He emphasised the PHEBUS-FP project as a major opportunity to examine chemical and physical forms taken by radionuclides during an accident. He also mentioned other projects, like ARTIST, which tested containment by-pass sequences (i.e. steam generator tube rupture [SGTR] severe accident sequences), Behaviour of Iodine Project (BIP) and Source Term Evaluation and Mitigation project (STEM), mainly dealing with iodine chemistry, and VERDON, which improved understanding of fission products released from fuel. Some key findings were highlighted:

- Releases from fuel were adequately predicted, except for tellurium (Te) and molybdenum (Mo). (It should be recognised that this statement is not shared by all Source Term workshop attendees.)
- Aerosol behaviour and transport was estimated reasonably, despite particles form remaining uncertain.
- Cs2MoO4 has been credited as the dominant chemical species transporting caesium to the containment and beyond.
- Long-run iodine concentration in the gas phase might not come from in-containment sumps, as previously assumed, and some other sources of organic iodine should be considered.
- Small particles might be formed from airborne iodine through oxidation in the containment gas phase.

To finish the presentation, Mr Lee listed the main areas where more research is considered necessary: deeper analyses of VERDON tests; iodine-paint interactions under realistic conditions (i.e. ageing, competition with other reactive species, doses); particles formed in the primary circuit; iodine interactions with water contaminants (complications associated to contaminated waters have not been thoroughly addressed so far). He highlighted the Fukushima Daiichi accident, for which forensic analyses have been conducted within the Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF) projects and are now conducted within the Analysis of Information from Reactor Buildings and Containment Vessels of Fukushima Daiichi Nuclear Power Station project (ARC-F), as a source of data that might help reduce model uncertainties.

L.E. Herranz (CIEMAT) presented “Last decade priorities: the SOAR perspectives”, based on the State-of-the-Art Reports issued by the Committee on the Safety of Nuclear Installations (CSNI) on Nuclear Aerosols (NEA, 2009) and Iodine Chemistry (NEA, 2007). In both cases, he focused on the remaining issues.

In the case of nuclear aerosols, Mr Herranz highlighted a number of issues, including: the shape of aerosols, which might be investigated through uncertainty and sensitivity analyses; aerosol resuspension, which might pose a threat in by-pass sequences; particle break-up, for which no data is available for prototypical nuclear aerosols; deposit revaporisation, which might have a potential impact in risk-dominant sequences; re-entrainment, which in case of contaminated pools reaching saturation conditions might turn into an unexpected late source of radioactivity. Other issues were mentioned but they were not discussed in the workshop’s final session.

In the case of iodine chemistry, some issues were also highlighted: the impact of chemical kinetics in radionuclide transport in the primary circuit; the large uncertainties in key conditions for iodine chemistry, like the sump pH; the adsorption/desorption of iodine onto/from containment surfaces; the production of organic iodides from any substrate and/or homogeneous reaction; and, the iodine chemical reactivity at the secondary side of a steam generator undergoing an SGTR severe accident sequence.

Some of the above issues have been tackled in recent experimental programmes, like BIP, STEM and Thermal-hydraulics, Hydrogen, Aerosols, Iodine (THAI), but others have yet to be addressed. Mr Herranz also emphasised that after the Fukushima Daiichi accident, the situation might have changed considerably and a longer time horizon should be borne in mind when discussing accidents, which might give rise to the so-called long-term effects.

M. Berdai (CNSC) presented “Use of PIRT in the assessment of Source Term (ST) phenomena” based on the PIRT-type studies conducted in Europe, Japan and the United States. She reviewed the bases of a PIRT exercise, emphasising its goal (identifying relevant phenomena to rank them according to their safety importance and current state of knowledge) and limitations (the interaction between phenomena is not thoroughly considered).

The European PIRT was conducted in the context of the EC EURSAFE (European expert network for the reduction of uncertainties in severe accident safety issues) project. It addressed the entire domain of severe accidents, retaining about 100 phenomena and selecting around 20 areas requiring further research. Among them was the oxidising impact on Source Term (particular reference to ruthenium volatilisation in the form of RuO_4). Updates on the PIRT have been provided periodically over recent years; this update did not follow the same quantitative method but it relied on the votes of an expert panel created for the purpose. In short, two major issues concerning Source Term were highlighted as deserving further attention (other issues being investigated at the time in international contexts like OECD projects were disregarded): fission product release and transport under oxidation conditions (in particular, air ingress for high burnup and MOX fuel with special attention to semi-volatile molybdenum and low volatile ruthenium) and high temperature chemistry in the reactor coolant system (RCS) as a need for processes like revaporisation.

The high-level American PIRT focused on a Station BlackOut (SBO) accident and was considered an integral phenomena assessment. The Figures of Merit (FOM) selected were the radiological consequences (essentially doses) and system/component operability in the BDBA (Beyond Design Basis Accident) domain. The scope was limited to three main areas: in-vessel melt progression, emergency core cooling system equipment performance and ex-vessel debris coolability and core-concrete interaction. Therefore, no major remark on Source Term was made, but it was agreed that uncertainties related to core degradation overshadow other sources of uncertainties. The study emphasised the need to perform human performance assessments and focus attention on instrumentation for severe accidents.

A specific Source Term PIRT based on findings during the Fukushima Daiichi accident was developed by Japan (Atomic Energy Society of Japan). The authors split the accident in three phases (early, middle and late) and set FOMs quite focused on Source Term: radionuclide release fractions, radionuclide chemical forms and release timing. It was developed on qualitative bases, mostly on expert judgement. They ranked in-vessel release-related phenomena to Source Term and condensation, revaporisation and adsorption phenomena as key mechanisms for radionuclide behaviour in the reactor pressure vessel, the primary circuit and the steam line.

In the concluding remarks, besides summarising the main ideas of the presentation, Ms Berdai offered recommendations, mainly related to the optimisation of the PIRT methodology.

2.2. Session 2: Recent progress and current status (Chaired by: N. Mesmous, CNSC)

The second session was designed to update everybody on the latest achievements made and the major findings from Fukushima related to Source Term. It consisted of three presentations:

- “Main experimental findings of recent investigations”;
- “Current predictive capability of Source Term”;
- “Key Source Term issues from Accident at Fukushima Daiichi Nuclear Power Station”.

S. Gupta (Becker Technologies [BT], Germany) presented, in collaboration with other organisations responsible for the latest experimental projects run on Source Term (French Alternative Energies and Atomic Energy Commission [CEA]; Canadian Nuclear Laboratories [CNL]; Institute for Radiological Protection and Nuclear Safety [IRSN, France]; VTT Technical Research Centre of Finland [VTT, Finland]), the “main experimental findings of recent investigations”. After reminding the group of the motivation behind Source Term experimental research and referring to the existing infrastructures, particularly in Europe, he classified the main findings according to: release, chemistry and transport in RCS and RCB (reactor containment building) and mitigation.

Fission product (FP) release was split according to in-vessel and ex-vessel phases of the accident. As for the in-vessel phase, the database (HEVA/VERCORS, PHEBUS-FP, etc.) has been enlarged with ISTP/VERDON tests and a classification has been proposed: volatile FPs (Noble Gases, Cs, I, Te and others), semi-volatile FPs (Mo, Ba, Rh, etc.), low volatile FPs (Sr, Ru, La and others), non-volatile FPs (Zr, Nd, Pr) and actinides (also non-volatiles). The presentation highlighted some major observations: higher release kinetics for volatile FPs for high burnup and MOX fuel in comparison to low burnup UO2 fuel, starting at a rather low temperature; substantial release in oxidising conditions for Mo (steam environment) and Ru (air ingress) and in reducing conditions for Ba. As for the ex-vessel phase, Ms Gupta stressed the potential relevance and incomplete knowledge of aerosol releases from boiling sumps. Special mention was made of delayed releases due to remobilisation of a fraction of fission product deposits, due to revaporisation, resuspension and/or revolatilisation. Very limited knowledge exists for these phenomena, as is the case for long-term FP leaching. As for transport through RCS, there are still some uncertainties affecting iodine and ruthenium speciation, related to the effect of various gaseous and aerosol species/impurities on the volatilisation of both elements. As for containment, in addition to iodine volatilisation from boiling pools (mentioned above), a reduced number of issues stand out over others (like FP interactions with PARs): formation of organic iodine from sources other than transfer from pools and reactions with paints and production and behaviour of small iodine oxide particles in the containment atmosphere. Finally, as for mitigation, the performance of safety systems under realistic conditions would notably strengthen their reliability under BDBA.

At the end of the presentation, Ms Gupta emphasised that given the time passed since the last NEA Working Group on Analysis and Management of Accidents (WGAMA) SOARs were issued it might be the right time for an update, or at least a technical report on key aspects not previously addressed such as nature and amount of potential water pool contaminants/impurities. Given the potential impact of this aspect on FP release and transport of some key radionuclides, this suggestion was supported by the WGAMA Chair.

Ch. Mun (IRSN), in collaboration with other code developers SNL/NRC, GRS and CNSC, prepared the presentation entitled “Current predictive capability of Source Term”. Once the broad features of the severe accident codes Accident Source Term Evaluation Code (ASTEC), ATHLET, ATHLET-CD and COCOSYS (AC2), MELCOR (SNL, United States), and Modular Accident Analysis Program (MAAP) were introduced, the presenter discussed in detail their approaches to FP releases, in-RCS and in-containment transport and chemistry and mitigation. Through the analysis of individual model approaches to releases, prevailing conditions and importance of FPs and control rod materials (no models available for structural materials in any of the codes), they identified some specific open issues: late in-vessel releases, ex-vessel molten pool releases, fuel leaching and accident-tolerant fuels (ATFs), among others. For the area of in-RCS transport and chemistry, remobilisation mechanisms and gaseous iodine generation mechanisms were considered to need further development. In containment, the areas identified for further study were iodine oxides reactivity, the production of gaseous organic iodides through homogeneous reactions, and natural containment leakages. Finally, the presenters emphasised that Uncertainty and Sensitivity Analysis (UaSA) at plant scale would be necessary to assess the dominating uncertainties and sensitivities of all the issues raised during the presentation.

Y. Maruyama (JAEA) presented the “Key Source Term issues from Accident at Fukushima Daiichi Nuclear Power Station”. After providing an overview of the implications of Source Term estimates in terms of emergency preparedness and severe accident mitigation, Maruyama noted it is important to keep enhancing predictive tools. The accidents unfolding in units 1-3 were characterised through the pressure evolution. The presentation highlighted the influence of upper structures on FP transport through the potential chemisorption of some species (CsOH) and later revaporisation. It also highlighted the effect of FP chemical speciation on transport and behaviour, stressing the importance of some boundary conditions, like pH in the suppression pool. Concerning ex-vessel phenomena, Maruyama said temperature and injection flow rates in suppression pools might have been higher than estimated in previous studies and did not rule out the possibility of having iodine species revolatilisation with the current knowledge of the accident scenarios, in which variables as important as suppression pool pH are not known. Another interesting point made was the strong effect of leak paths definition between RCV and containment and between containment and reactor building; both definition of flow-paths and phenomena governing the transport and deposition of particles entail huge uncertainties. At the end of the presentation, other issues were discussed, like the FP leakage through aquatic pathways and what might happen during a severe accident in a spent fuel pool.

2.3. Session 3: Concluding session (Chaired by: L.E. Herranz, CIEMAT; D. Jacquemain, IRSN)

The last session was devoted to the synthesis and discussion of the main issues raised during the previous ones. Two presentations were given:

- " Summary of discussions @ Workshop on Source Term";
- "Main open issues and possible ways forward".

R. Lee (NRC) highlighted four major points concerning Source Term in "Summary of discussions @ Workshop on Source Term" that are essential for NRC at the present time. The first was the role of severe accident analysis (MELCOR) to assess the efficacy of mitigation systems in the Defence-in-Depth approach and the siting and emergency planning, the safety issue resolution, the risk-informed decision making and the testing of Severe Accident Management Guidelines (SAMGs) effect. The second focused on iodine chemistry and particularly on specific aspects of the iodine interaction with paints and the need to understand how to extrapolate iodine research findings to actual plants. The third concerned the modelling techniques used in aerosol transport in the RCS, the enhancement of numerics, the potential effect of "fractal" collision kernels or the actual nature of aerosols (can PHEBUS-FP observations be adopted as fully prototypical?). And fourth, radionuclide releases and behaviour in New Generation of Nuclear Power (NGNP). In addition, the Uncertainty Quantification (UQ) approach to be used in severe accident analysis, particularly in the frame of new Source Term to be defined in high burnup and MOX fuels, was highlighted as a key element in the forthcoming research on Source Term.

D. Jacquemain (IRSN) synthesised the "Main open issues and possible ways forward" in Source Term research according to the preceding presentations with the intention to spark discussion on future investigations. The key points identified are:

- Delayed FP releases by remobilisation phenomena. Observed in Fukushima and proved in Source Term experiments, this potential contribution to radiological releases is worth investigating in multiple ways (revaporisation, revolatilisation, reentrainment and resuspension). As a first step, a review of existing knowledge and data is proposed before launching any experimental investigation.
- Fine particle behaviour in containment. Several mechanisms can produce microscopic particles, which have the potential to remain airborne, interact with iodine, affect (and be affected by) safety systems, and are more difficult for filtration systems to retain. The group recommended conducting experimental investigations after reviewing the current knowledge and data available.

- Organic iodides (OrgI) in containment. Despite the efforts made in the latest experimental programmes to identify the major sources of OrgI, there is evidence that something is still missing in the current modelling to match observations made in the long-run in PHEBUS-FP tests. In this case, before launching any experimental venture, it was recommended to review all the data available and carefully set the right conditions to investigate other routes of OrgI formation. It should be noted that there is not a consensus among iodine experts on the phenomena to investigate, i.e. whether there is or is not a homogeneous reaction between organics and iodine in the gas phase.
- FP release. Even though there has been significant progress in research, there are some areas worth further effort. This is the case of SGTR and LOCA sequences, which will be investigated in the H2020 R2CA project. What seems to be drawing more attention after the Fukushima Daiichi accident are the so-called long-term releases that strongly depend on the core degradation phenomena and fuel leaching. These issues would need at least a review of existing models to assess the current predictive capabilities. A different matter is the need to investigate releases from the ATFs, which should be articulated consistently with other ongoing initiatives on ATF research.
- Pool scrubbing. As highlighted in the European Commission Passive and Active Systems on Severe Accident Source Term Mitigation project (EC PASSAM) project, this issue lacks a systematic approach and a full-scope investigation addressing conditions as yet explored, with a particular emphasis on saturated pools and high injection velocities. In this research, a deep study of hydrodynamics is recognised to be of vital importance. The NUGENIA Integration of Pool scrubbing Research to Enhance Source-term Calculations project (IPRESCA) project is currently being conducted, so no specific recommendation was given at this time.
- High temperature chemistry in RCS. This issue has been investigated experimentally and new models addressing control rod effect (Sg/In/Cd allow and B) on fission product transport are presently being developed. Given the current status, no specific recommendation was made at this time.

Beyond the specific issues listed above the group highlighted a few more points to consider in any ST research initiatives launched in the future:

- The need to address realistic conditions such as the presence of impurities in the system, the multicomponent nature of aerosols, the high temperature and doses anticipated, the boiling conditions in sumps, and, more importantly, scaling the results to nuclear power plants.
- The key information expected from projects like H2020 Management and Uncertainties in Severe Accidents (MUSA) project and IAEA Coordinated Research Project (CRP) on uncertainties. These two projects will bring insight into the sources of uncertainties dominating Source Term estimates and, as a consequence, they should be instrumental in defining research in the mid-term, as the outcomes are expected no earlier than 2023.
- The key role played by leak pathways when analysing accident sequences. System failures and leaks play an outsized role in any Source Term prediction on the environment. Any reduction of uncertainties affecting leak path definition in a severe accident analysis would have a strong effect on the results. This issue might

be worth bringing to the attention of the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) for potential work together with the WGAMA or even a joint project preparation in the context of the NEA.

3. Conclusions

The structure of the Workshop on Source Term met its main goals: identifying the remaining safety-significant uncertainties on Source Term (ST) and proposing how they should be addressed. The invited lectures met the highest possible expectations. They were comprehensive and included discussion elements that the attendees appreciated and paid attention to, both at the end of each presentation and in the final discussion held in the last Workshop session.

Generally speaking, a reasonable consensus was reached on the issues that are still “open”, although discussions could have been more detailed on some specifics, like the instrumentation that should be used to investigate experimentally the different issues. On the other hand, the tools needed to approach the investigations (Nuclear Energy Agency [NEA] research projects, State-of-the-Art Reports [SOARs], Phenomena Identification and Ranking Table [PIRTs], International Standard Problems [ISPs], and more) were discussed extensively, which should be sufficient to properly address the issues identified. It should be noted that despite the fact that some issues are still open, some attendees felt that there was a need for a peer review of existing data. Some felt that the database could be further exploited; others suggested that some of the data used for model development and validation might not be directly applicable.

The open issues requiring further investigation can be summarised as follows (a list supported by most of the attendees):

- remobilisation phenomena (delayed releases);
- fine particles (sources, behaviour and mitigation);
- organic iodides (completion of the existing database);
- fission product leaching (from the accident to decommissioning).

It should be emphasised that even if some new experimental projects are launched in the short run, actions should be put in place to better exploit the data available with the intention of bringing them to their maximum usefulness for plant applications. In addition, any experimental programme should pay due attention to aspects like the representativeness of data for realistic conditions (“dirty water” included) and scaling issues.

In addition to the open issues listed above, there are others of a certain interest, like high temperature chemistry and pool scrubbing, that are being addressed in other contexts and do not need further actions until the ongoing work is finished. Another emerging matter that should be given some attention is the potential Source Term that might come out of accident-tolerant fuels (ATFs), particularly those of first generation that can be considered a development of the fuels currently used in nuclear power plants.

Even though without a specific formulation on which type of activity should be carried out, but with the conviction that something should be put in place (maybe as a collaboration between the NEA Working Group on Integrity and Ageing of Components and Structures [WGIAGE] and the NEA Working Group on Analysis and Management of Accidents

[WGAMA]), it was generally agreed that leak paths during severe accidents should be in the ST research agenda.

Finally, it was agreed that the application of Best Estimate Plus Uncertainties methods in severe accidents, particularly if Source Term variables are adopted as Figures of Merit, will bring essential insight concerning the most necessary research in the mid-term. High expectations are placed on the H2020 Management and Uncertainties in Severe Accidents (MUSA) project and the Coordinated Research Project (CRP) of the IAEA. In fact, a good initiative would be to ensure a close link between these projects and the WGAMA during the coming years.

4. References

NEA (2009), “State-Of-the-Art Report (SOAR) on Nuclear Aerosols (NARSOAR)”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_18750.

NEA (2007), “State of the Art Report (SOAR) on Iodine Chemistry”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_18434.

Annex A. Workshop agenda

Monday 21 January 2019, Room BB2

Welcome & opening remarks 9:00-9:10

(L. Herranz, CIEMAT; N. Sandberg, OECD/NEA)

Session 1	**Key Source Term Background** Session Chair: Y. Maruyama (JAEA)		
1.1	Recent key milestones (and findings): From PHEBUS-FP to present times	(R. Lee, NRC)	9:30-10:00
1.2	Last decade priorities: the SOAR perspectives	(L. Herranz, CIEMAT)	10:00-10:30
1.3	Use of PIRT in the assessment of Source Term (ST) phenomena	(M. Berdai, CNSC)	11:30-12:00
1.4	Session 1 Discussion		12:00-12:30
Session 2	**Recent Progress and Current Status** *Session Chair: N. Mesmous (CNSC)*		

2.1	Main experimental findings of recent investigations	(S. Gupta, BT)	13:45-15:00
2.2	Current predictive capability of Source Term	(C. Mun, IRSN)	15:00-16:15
2.3	Key Source Term issues from Accident at Fukushima Daiichi Nuclear Power Station	(Y. Maruyama, JAEA)	16:45-17:30

End of day 1

Tuesday 22 January 2019, Room BB2

Session 3 **Concluding session**

Session Chairs: L. Herranz (CIEMAT), D. Jacquemain (IRSN)

3.1	Summary of discussions @ Workshop on Source Term	(D. Jacquemain, IRSN)	9:00-9:30
3.2	Final discussion	(all)	10:00-10:30
3.3	Main open issues and possible ways forward	(L. Herranz, CIEMAT)	11:00-12:00

End of the workshop

Annex B. List of participants

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Dr Martina ADORNI	BEL V (subsidiary of FANC), Brussels
Mr Philippe DEJARDIN	Tractebel (ENGIE), Brussels
Mr Thibaut HELMAN	Tractebel (ENGIE), Brussels
Mr Thibaut VAN ROMPUY	BEL V (subsidiary of FANC), Brussels

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Mr Glenn GLOWA	Canadian Nuclear Laboratories, Chalk River, Ontario
Mr Noreddine MESMOUS	Canadian Nuclear Safety Commission, Ottawa, Ontario
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