

## Summary of SARNET achievements

Thierry ALBIOL<sup>1</sup>, Tim HASTE<sup>2</sup>, Jean-Pierre VAN DORSSELAERE<sup>1</sup>, Christophe JOURNEAU<sup>3</sup>, Leonhard MEYER<sup>4</sup>, Bernard CHAUMONT<sup>1</sup>, Bal Raj SEHGAL<sup>5</sup>, Bernd SCHWINGES<sup>6</sup>, David BERAHA<sup>6</sup>, Alessandro ANNUNZIATO<sup>7</sup>, Roland ZEYEN<sup>8</sup>

- 1) Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France
- 2) Paul Scherrer Institute (PSI), Switzerland
- 3) Commissariat à l'Énergie Atomique (CEA), France
- 4) Forschungszentrum Karlsruhe GmbH (FZK), Germany
- 5) Kungl Tekniska Högskolan (KTH), Sweden
- 6) Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Germany
- 7) Joint Research Centre (JRC) Ispra, Italy
- 8) Joint Research Centre (JRC) Petten - Cadarache, France

CONTRACT SARNET FI6O-CT-2004-509065

### Summary

Fifty-one organizations cooperate within SARNET (Severe Accident Research NETWORK of Excellence) joining their capacities of research in order to resolve the most important pending issues for enhancing, in regard to Severe Accidents (SA), the safety of existing and future Nuclear Power Plants (NPPs). This project, co-funded by the European Commission (EC) within the 6<sup>th</sup> Framework Programme, has been defined in order to optimise the use of the available means and to constitute sustainable research groups in Europe. SARNET tackles the fragmentation that may exist between the different national R&D programmes, by defining common research programmes and developing common computer tools and methodologies for safety assessment. SARNET comprises most of the actors involved in SA research in Europe, plus Canada.

To reach these objectives, all the organizations networked in SARNET contribute to a Joint Programme of Activities (JPA), which consists of:

- Implementing an advanced communication tool for accessing all project information, fostering exchange of information, and managing documents;
- Harmonizing and re-orienting the research programmes, and defining new ones;
- Analyzing the experimental results provided by research programmes in order to elaborate a common understanding of relevant phenomena;
- Developing the ASTEC code (integral computer code used to predict the NPP behaviour during a postulated SA), which capitalizes in terms of physical models the knowledge produced within SARNET;
- Developing Scientific Databases, in which all the results of research programmes are stored in a common format (DATANET);
- Developing a common methodology for Probabilistic Safety Assessment of NPPs;
- Developing short courses and writing a text book on SA for students and researchers;
- Promoting personnel mobility amongst various European organizations.

This paper presents the major achievements at the end of the project, after four and a half years of operation of the network, in terms of knowledge gained, of improvement of the ASTEC reference code, of dissemination of results and of integration of the research programmes conducted by the different partners.

## A. GENERAL PRESENTATION OF SARNET

The Nuclear Power Plants (NPPs) existing in Europe are designed with the principles of defence in depth. In particular, they incorporate a strong containment and engineering systems to protect the public against radioactivity release for a series of postulated accidents. Nevertheless, in some very low probability circumstances, severe accident (SA) sequences may result in core melting and plant damage leading to dispersal of radioactive material into the environment and thus constituting a health hazard to the public.

In 2004, many achievements had been already obtained in the field of research on Water Reactor SA, thanks in particular to the numerous European actions undertaken within the 4<sup>th</sup> and 5<sup>th</sup> Framework Programmes (FP) of the European Commission (EC). In spite of the accomplishments reached, several issues were remaining where research activities were needed in order to reduce further uncertainties considered of importance and to consolidate severe accident management plans [1].

Research programmes on SA were - and still are - decided at national levels. Co-operation agreements are often concluded around these national programmes, but on a case-by-case basis. Facing the inevitable reduction of the national budgets in this field, it was necessary to coordinate better the national efforts to optimise the use of the available expertise and experimental facilities in order to resolve the remaining issues for enhancing the safety of existing and future NPPs.

Therefore, since April 2004, fifty-one organizations involved in R&D in SA, including technical safety organizations (TSOs), industries, utilities and universities, decided to seize the opportunity offered by the 6<sup>th</sup> FP of the EC to network in SARNET (Severe Accident Research NETwork of Excellence) their capacities of research in the SA area in a durable way. These organizations are coming from 18 Member States of the European Union (Austria, Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, the Netherlands, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom), Switzerland, Canada and the Joint Research Centres of the EC (Fig. 1). The network benefits from, and strengthens, the existing complementarities between the different partners (corium / fission product chemistry experts, small scale / large scale testing, simulants / real materials, experimentalists / model developers / code developers) [2].

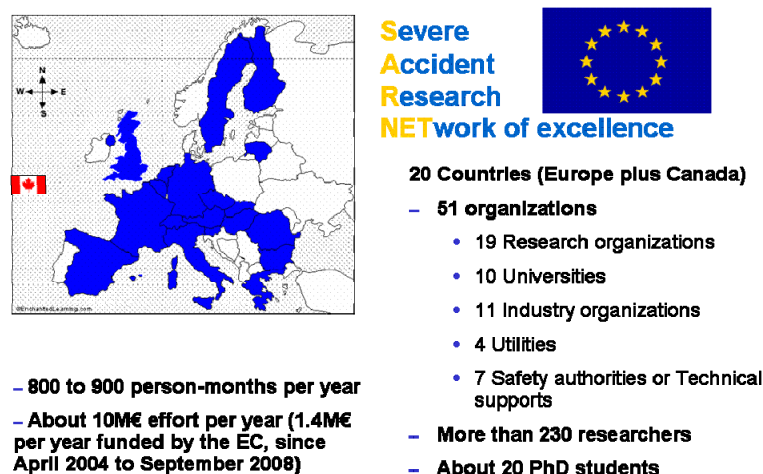


Figure 1: SARNET General Features

### Session 5: Conclusions and Perspectives. Paper 5-2

The general objectives of SARNET consist of:

- Tackling the fragmentation that exists between the different R&D organizations, notably in defining common research programmes and developing/qualifying computer tools;
- Harmonizing the methodologies applied for assessing risk and improve Level 2 Probabilistic Safety Assessment (PSA) tools;
- Disseminating the knowledge to Newcomers to the European Union more efficiently and associating them with the definition and the conduct of research programmes more closely;
- Bringing together top scientists in SA research to constitute a world leadership in advanced computer tools for SA risk assessment.

To achieve these objectives a Joint Programme of Activities (JPA) has been defined and yearly updated. All the organizations networked in SARNET contribute to the JPA, which is broken down into twenty work-packages (Fig. 2) which can be presented in three elements:

- Integrating activities to strengthen links between organizations;
- Joint research activities to resolve remaining outstanding issues;
- Spreading of excellence activities to diffuse the knowledge.

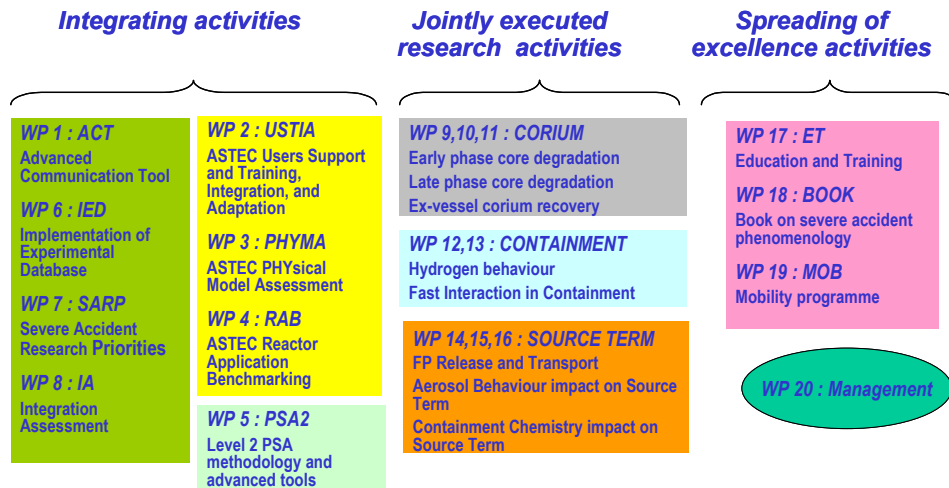


Figure 2: SARNET Joint Programme of Activities

This paper presents the major achievements after four and a half years of operation of the network, in terms of knowledge gained, of improvement of the ASTEC reference code for SA, of dissemination of results and of integration of the research programmes conducted by the different partners.

## B. MAIN ACHIEVEMENTS

The main achievements, as at the end of the project, are summarised below.

### B.1 Integrating Activities

The integrating elements of the programme are considered of highest importance and constitute key elements of the JPA.

## Session 5: Conclusions and Perspectives. Paper 5-2

An Advanced Communication Tool (ACT) has been implemented for enabling communication between project partners and for document management. ACT is a key concept to achieve SARNET goals: today's portal technology provides unified support for efficient collaboration within the network, in particular:

- Access, search, publication of documents and codes (concept of knowledge storage),
- Contact and communicating with partners (interactive and collaborative services),
- Joint co-ordination of actions/programmes (co-operative management of the network),
- List of links to satellite community projects (R&D projects, related sites).

The ACT platform has been realized on the basis of MS Sharepoint Portal Server. Access is given by Web Browsers, enabling logging in from any Internet connection. Around 250 users of SARNET have been granted access to this tool, and the ACT is used intensively and efficiently: e.g. 500 to 1000 accesses per month, 8000 items stored (Fig. 3).

Besides, a public Web site ([www.sar-net.org](http://www.sar-net.org)), providing major information on SARNET, has been implemented.

DATANET, the SARNET experimental database network, has been developed and maintained to ensure preservation, exchange and processing of SA experimental data, including all related documentation. The data are both existing experimental data that SARNET partners are willing to share within the network and all new data produced within SARNET. DATANET is based on the STRESA tool developed by JRC Ispra and consists of a network with several local databases (or nodes). From the central database, it is possible to connect with other local databases; direct connections to the local databases are also possible, which increases the potential and the power of this type of system. Currently, nine nodes exist: the central one at JRC Ispra, and local ones at FZK, IRSN, CEA, CIEMAT, FORTUM-VTT, AEKI, KTH and GRS. Training weeks have been periodically organized at JRC Ispra. The results of more than 100 experiments have been implemented so far (Fig. 3).

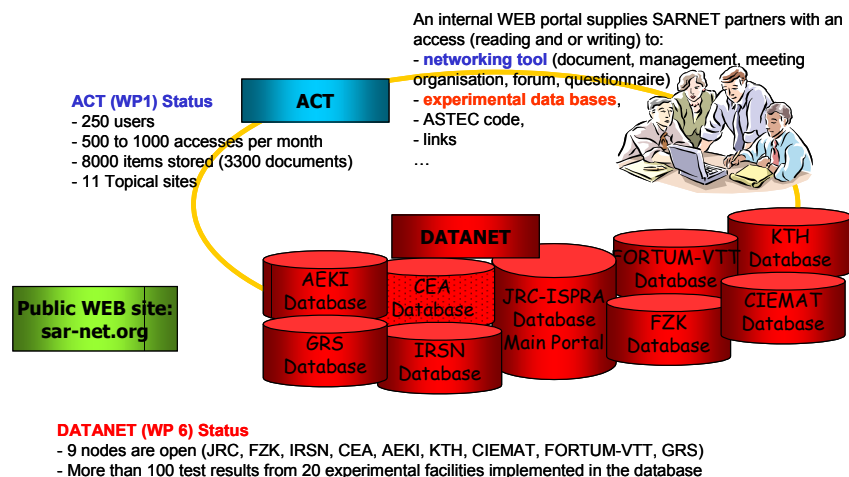


Figure 3: SARNET Information Systems

The SA integral code ASTEC [3], jointly developed by IRSN and GRS, is the main integrating component and contributes efficiently to the dissemination of the knowledge. Furthermore, most of the “Joint Research Activities” are linked to ASTEC, as one of their ultimate goals is to provide physical models to be integrated in ASTEC. The exchange of information on the detailed models developed by the various experts through interpretation of experiments leads to generic common models in the different detailed codes (examples of

**Session 5: Conclusions and Perspectives. Paper 5-2**

ICARE/CATHARE and ATHLET-CD for core degradation). Model improvements for the ASTEC code are then derived from these detailed models.

Twenty-eight organizations have collaborated with IRSN and GRS on the code development and assessment. ASTEC describes the behaviour of a whole NPP under SA conditions, including SA Management by engineered safety systems and procedures. It is intensively used by IRSN for Level 2 PSAs for 900 and 1300 MWe PWRs and by GRS for their PSA2 consolidation study for Konvoi 1300 MWe reactors. Besides, more and more partners use it for complete accident scenario calculations.

A close and efficient collaboration between ASTEC users and developers has been set up using ACT and the MARCUS web tool for code maintenance. Training courses on code use were organized. Three main code versions were released to the partners: V1.1 mid-04, V1.2 mid-05 and V1.3 end of 2006 (the latest V1.3 rev2 update being released in Dec.07). The code documentation has been greatly improved since the beginning of SARNET. Three ASTEC Users' Club meetings, the latest being held in April 2008, allowed fruitful direct discussion between users and developers.

Model improvements were performed by CEA on corium behaviour in lower head and on vessel external cooling, including validation on LIVE, SULTAN and ULPU experiments. Other models were proposed or improved after discussion between partners, for instance: release of Silver-Indium-Cadmium and of ruthenium from the core, B<sub>4</sub>C oxidation, iodine mass transfer and radiolytic oxidation in containment (see details or other examples in part B.2). Other improvements are planned in the near future like aerosol mechanical resuspension in the circuits. ASTEC was also used for preparing and interpreting several experiments such as QUENCH and LIVE in FZK. The model adaptations to BWR and CANDU were specified and ranked, along with promising scoping calculations with the present code versions.

An extensive code validation was carried out by the partners on 65 experiments (analytical and integral ones), often OECD International Standard Problems. Generally, the results can be ranked as good, even very good for circuit thermal-hydraulics, core degradation and fission products and aerosol behaviour. Many plant applications were performed on various NPPs (French PWR, Konvoi 1300, Westinghouse AP 1000, VVER-440, VVER-1000 and RBMK) and various SA scenarios, including benchmarks with other codes. The agreement was good with the integral codes MELCOR and MAAP4 on the trends and orders of magnitude of the main sequence results, and very good with detailed results of mechanistic codes such as CATHARE for circuit thermal-hydraulics and as ATHLET-CD and ICARE/CATHARE for core degradation. ASTEC numerical robustness has been significantly improved since the beginning of SARNET.

IRSN and GRS are now taking into account all users' requirements on ASTEC evolution for the new series of ASTEC V2 versions. The first of these, V2.0, to be released in March 2009, will be applicable to the EPR, in particular its core-catcher, and will include the ICARE2 (IRSN code for core degradation) mechanistic models.

Harmonization of Level 2 PSA methodology and development of advanced tools is also an integrating activity. Level 2 PSA is a powerful tool to assess plant-specific vulnerability regarding NPP SA. It evaluates possible SA scenarios in terms of frequency, loss of containment integrity and radioactive release into the environment and quantifies the contribution of prevention and mitigation measures in terms of risk reduction. Different approaches are used in Europe, derived more or less from what has been implemented in the USA. A description and comparison of the main elements of methods used by the different

### Session 5: Conclusions and Perspectives. Paper 5-2

partners to develop their PSA has been written. For many issues regarding Level 2 PSA, questionnaires have been set up and the answers have been analyzed in order to define next steps of harmonization. Case studies for harmonization have then been performed on specific issues as hydrogen combustion, iodine chemistry, melt corium concrete interaction (MCCI), large early releases, reactor safe state definitions and methods for level 1 and 2 PSA interface. A certain level of harmonization has been reached and recommendations have been written. A State of the Art Report on Dynamic Reliability methods has been produced and the limitations of classical methods, which could be exceeded using these reliability methods, were identified. Examination of the benefit of one of the possible methods (Monte Carlo Dynamic Event Tree) has been achieved for the station blackout situation. Large efforts were dedicated to a benchmark exercise (quantification of the risk of containment failure induced by the activation of safety systems during the vessel core degradation phase). This benchmark allowed the comparison of dynamic reliability methods with classical ones. Finally, a precise definition of ASTEC requirements for level 2 PSA needs and work on ASTEC coupling with probabilistic codes are ongoing.

The Severe Accident Research Priority (SARP) work-package allowed to identify research priorities with the aim of re-orientating progressively the existing national programmes and of contributing to launch new ones in a coordinated way, eliminating duplications and developing complementarities. This activity was performed in close collaboration with participants, representing TSOs, industry and utilities. As in the Phenomena Identification and Ranking Table (PIRT) carried out in EURSAFE [1], the whole spectrum of SA situations, extending from core uncovering to long term corium stabilization, long term containment integrity, and fission product release to the environment was considered. Special attention was brought to a risk oriented approach in order to really focus on the most relevant pending issues. As a result, a consensus was reached and 18 main issues were ranked into four categories.

Six issues are regarded to be investigated further with **high priority**:

- core coolability during reflood and debris cooling,
- ex-vessel melt pool configuration during MCCI and ex-vessel corium coolability by top flooding,
- melt relocation into water, ex-vessel Fuel Coolant Interaction (FCI),
- hydrogen mixing and combustion in containment,
- oxidising impact (Ru oxidising conditions/air ingress for high burn-up and MOX fuel elements) on source term,
- iodine chemistry in Reactor Cooling System (RCS) and in containment.

Four issues are assessed with **medium priority**; these items should be investigated further as already planned in the different research programmes. The risk significance is reduced due to considerable progress of knowledge, but some questions are still open:

- hydrogen generation during reflood and melt relocation in vessel,
- corium coolability in lower head,
- integrity of the Reactor Pressure Vessel due to external vessel cooling,
- direct containment heating.

For five issues the current knowledge is considered as sufficient assessing the state of knowledge and the risk and safety relevance and taking into account ongoing activities: these issues are assessed with **low priority**, they could be closed after the related ongoing activities are finished:

- corium coolability in core catcher with external cooling,

## Session 5: Conclusions and Perspectives. Paper 5-2

- corium release following vessel rupture,
- crack formation and leakages in concrete containment,
- aerosol behaviour impact on source term (in steam generator tubes and containment cracks),
- core reflooding impact on source term.

Three issues are marked as “**issue could be closed**”. Due to the risk significance and the current state of knowledge, which is regarded as sufficient in comparison to other issues with greater risk relevance and larger uncertainties, no further experimental programme is needed:

- integrity of RCS and heat distribution,
- ex-vessel core catcher and corium-ceramics interaction, cooling with water bottom injection,
- FCI including steam explosion in weakened vessel.

This ranking of issues will allow redistribution of competence and manpower on high priority issues, both in the EC 7<sup>th</sup> FP and in other international projects (e.g. OECD projects).

### B.2 Jointly Executed Research Activities

These activities constitute the R&D basis of the network. Linked to the above research priorities, they aim at resolving the priority pending issues. They are split into three areas: corium behaviour, containment integrity and source term.

In all three areas, the same method has been adopted: review and selection of available relevant experiments, synthesis of analyses and interpretation of data from these experiments, and model review, synthesis and proposals of new or improved models for ASTEC.

#### B.2.1 Corium

Corium behaviour is a large topic dealing with more than half of the issues selected in the EURSAFE PIRT [1]. The corium area ranges from early phase of core degradation to late phase core degradation and ex-vessel corium stabilization. A major effort is also underway on the development and improvement of the corium thermodynamic and material physical property databases. Joint activities have been deployed in 22 SARNET organizations [4], such as the contribution to the definition and the interpretation of tests, with benchmark exercises and associated model improvements: OECD-CCI tests around the MCCI programme; QUENCH-10 test on air ingress in bundle geometry; QUENCH-11 test on boil-down and quench; QUENCH-12 test with VVER bundle; COMET-L1 and L2 tests to study MCCI in 2D geometry; LIVE or VULCANO-COMET tests. Similar activities have been carried out for ongoing and new projects from the International Science and Technology Centre (ISTC): PARAMETER project on core top flooding models, METCOR on the impact of thermo-mechanical interaction on the vessel behaviour, CORPHAD on the corium thermodynamic (improvement of the NUCLEA database). In the International Source Term Programme (see Source Term part below), FZK and IRSN have harmonized their test matrices on Zircaloy oxidation by air/steam mixtures and on B<sub>4</sub>C oxidation and degradation.

Among the main achievements on the corium activities [4], we can quote as examples:

- The understanding of the oxidation phenomena in steam and in air has progressed and oxidation correlations have been validated. The importance of material composition has been demonstrated. Further research is required on new cladding materials, especially in relation to the hydrogen and fission product source term issues.

### Session 5: Conclusions and Perspectives. Paper 5-2

- Data on B<sub>4</sub>C oxidation have been collected, thanks to experiments at FZK and IRSN, which allows a common interpretation of the integral test PHEBUS FPT3.
- The launching of the late-in-vessel LIVE experiments has started a new series of modelling and analytical work on in-vessel melt pool behaviour.
- The different models of vessel failure by creep rupture have been compared and a common understanding of the OECD OLHF-1 test has been achieved. Modelling of the crack evolution is in progress.
- 2D debris bed coolability analyses for inhomogeneous bed structures showed an increased coolability compared to earlier 1D particle beds. This launches a new interest in this issue both experimentally and numerically including a pursuit of the debris bed formation and its characteristics of coolability importance.
- Likewise, the recent 2D MCCI test gave unexpected results with a marked ablation anisotropy for silica-rich materials. Interpretation and modelling of this behaviour must be pursued.
- Core catcher concepts based on spreading (EPR) and bottom flooding (COMET, down-comers) are being studied and progress has been achieved in their modelling.
- The validation of the chemical thermodynamics database NUCLEA has been extended thanks to the analysis of EC-funded experiments and a round-robin exercise has qualified the uncertainties of energy dispersive X-ray spectrometry (EDX) analyses.

#### ***B.2.2 Containment***

The research efforts on energetic phenomena that could potentially threaten containment integrity concern hydrogen behaviour and fast interactions in the containment. For the former, the hydrogen combustion and associated risk mitigation is studied, concentrating on the formation of combustible gas mixtures, local gas composition and potential combustion modes, including reaction kinetics inside catalytic recombiners. Hydrogen distribution within the containment is studied to assess the risk of high concentrations.

Experimental programmes on hydrogen combustion with gradients (ENACCEF, IRSN) and recombiner kinetics (REKO-3, FZJ) have been performed and/or are ongoing. ENACCEF experimental results have been used in a benchmark using 3 different 3D Computational Fluid Dynamic (CFD) codes (FLUENT, TONUS-3D and REACFLOW). The results revealed some weaknesses of the combustion models used when simulating combustion with negative hydrogen gradient. Further experiments in the ENACCEF facility will focus on the interaction of hydrogen flames with sprays. New tests in REKO-3 are focused on the gas ignition on hot catalyst elements. The results will be used for the validation of numerical codes.

The major achievement in the topic of containment atmosphere mixing is the simulation of containment spray experiments that were performed in small scale (TOSQAN, IRSN) and large scale (MISTRA, CEA) facilities. Both atmosphere depressurization and stratification break-up phenomena were addressed. Experiments were simulated using CFD and lumped parameter codes. The calculated results demonstrated the feasibility of such simulations, which could also be applied to actual containments, provided that sufficient computing capacities are available. Apart from that, CFD simulations of the operation of Passive Autocatalytic Recombiners (PAR) in simplified 2D containment models represent a first significant step towards comprehensive simulations of PAR-atmosphere interaction in real plants. Finally, simulations of condensation experiments, performed in the CONAN (Univ. Pisa) facility allowed the comparison and assessment of different steam condensation models

### Session 5: Conclusions and Perspectives. Paper 5-2

that are used in CFD codes and significantly influence the behaviour of the simulated atmosphere.

Concerning fast interactions, FCI is studied to increase the knowledge of parameters affecting steam explosion energetics during corium relocation into water, and determine the risk of vessel or containment failure by investigation of specific processes like premixing, melt fragmentation and particle heat transfer mode. The work on FCI in SARNET was closely linked to Phase 1 of the OECD/SERENA programme, which had the objective of evaluating the capabilities of the current generation of FCI computer codes to predict steam explosion loading of the reactor structures and reaching consensus on the understanding of important FCI phenomena relevant to reactor situations [5]. Mainly, MC3D and IKEMIX/IDEMO have been used for this purpose. In addition a number of experiments were performed in MISTEE and DEFOR (KTH), and KROTOS re-started at CEA-Cadarache after moving from JRC-Ispira, with the aim to complement understanding of fragmentation and explosion behaviour of corium melts. The main accomplishment was a consensus that in-vessel steam explosion would not induce failure of the vessel, thus closing the in-vessel steam explosion issue from the risk perspective, and that ex-vessel steam explosions could induce some damage to the cavity. However, the level of loads in the latter could not be predicted due to a large scatter of the results. Major reasons of this scattering were found to be the uncertainties on void distribution in the pre-mixing region, inducing large discrepancies on the initial conditions of the explosion, and on explosion behaviour of corium melts, inducing more or less arbitrary tuning of the explosion parameters. These uncertainties will be addressed experimentally and analytically in Phase 2 of OECD/SERENA programme and in SARNET2.

The second issue concerning fast interactions is Direct Containment Heating (DCH). This includes melt dispersion into various reactor compartments, heat transfer and chemical processes such as production and combustion of hydrogen. The consequences of DCH are essentially related to cavity geometry; therefore a database has been established for the plant types EPR, French PWR-1300, VVER-1000 and the German Konvoi by an experimental programme performed in the DISCO-facilities (FZK). For EPR and VVER1000 plants the DCH issue can be considered as closed, due to their cavity design. The efforts to improve the predictive capabilities of the CFD code MC3D on the one hand and the system codes COCOSYS and ASTEC on the other hand will be continued. Benchmark exercises have revealed severe deficiencies in the current modelling: debris dispersion correlations need to be better adapted to the respective cavity geometries and oxidation and hydrogen combustion models are needed as they are the really challenging phenomena as regards containment integrity (experimental results showed that direct thermal effects alone should not endanger the containment integrity). Based on available experimental data from separate effect tests in DISCO, the scaling of combustion of hydrogen jets in an air-steam-hydrogen atmosphere must be established by applying dedicated combustion codes (COM3D, REACFLOW), then the modelling parameters must be transferred to codes with DCH models (CFD codes or COCOSYS) and finally adapted to ASTEC.

#### ***B.2.3 Source Term***

In the Source Term area, fission product release, transport and deposition were studied, including air ingress (the influence of an oxidising environment on release and circuit phenomena). For transport and deposition, one study focused on iodine, both its volatility in the primary circuit (particularly, for interaction with concomitant release of Ag/In/Cd) and its gas-liquid partitioning in the containment (also extended to ruthenium), while the other looked at aerosol behaviour in scenarios of special significance for risk: by-pass sequences

**Session 5: Conclusions and Perspectives. Paper 5-2**

(particularly, Steam Generator Tube Rupture (SGTR)), through-containment cracks and thermal and mechanical remobilization. The main achievements were detailed in [6].

Extensive effort was devoted to the continuing experimental International Source Term Programme (ISTP) launched by IRSN, CEA and EDF with the support of the EC [7]. Interpretation of available AECL and of RUSSET (AEKI) data showed that Ru release occurs in oxide form after an incubation period during which full oxidation of fuel and cladding occurs. RUSSET and VTT tests showed that oxide forms can stay volatile enough in lower temperature regions to be transported to the reactor containment in a stable volatile form, a very significant result. These tests continue. Test conditions in the future VERDON programme (CEA) [7] are being defined through air ingress reactor scenario simulations. These new data will be used to validate independently the improved ASTEC modelling. The ISTC VERONIKA experiment proposal on fission product release from highly irradiated VVER fuel was reviewed and SARNET proposals on the test matrix were adopted; this followed a similar exercise with the EVAN iodine chemistry project, whose results are now under evaluation. FIPRED experiments (INR) provided data on UO<sub>2</sub> pellet self-disintegration.

Concerning fission product transport, IRSN interpreted iodine chemistry in the circuit, based on data from PHEBUS FP, and VERCORS HT (CEA). Under reducing conditions, and without absorber material, it seems relatively straightforward, the iodine being transported mainly as caesium (and rubidium) iodide. In oxidizing conditions it is more complicated since Cs take-up in forms other than CsI affects the chemistry. Hence, iodine can either still be principally CsI or tends to form other metal iodides such as with control rod materials or, if these are not present, conditions become conducive to HI formation. These statements still need to be confirmed. The experimental CHIP programme (IRSN) [7] is providing kinetic and thermodynamic data on iodine transport through the primary circuit, particularly concerning key systems such as {I-Cs-O-H}, which will be used to improve ASTEC models, and help in the scaling of experimental results to reactor conditions. VTT are providing experimental support. In the QUENCH-13 bundle test (FZK), performed with strong experimental (PSI, AEKI) and modelling (PSI, GRS, EDF) support, with associated small-scale tests, production of Ag/In/Cd aerosols following PWR control rod failure was measured continuously for the first time, along with speciation at intervals. These data are being correlated with the core degradation and with earlier analytical tests EMAIC (CEA). Post-test calculations are being performed on this and on PHEBUS FP data; model improvements will be carried out as required.

Several facilities investigated aerosol retention within the steam generator under SGTR conditions: PSAERO/HORIZON (VTT), PECA/SGTR (CIEMAT) and ARTIST 5FWP (PSI). Overall, these tests showed that wet scenarios (those with the breach under the secondary side water level) would provide effective scrubbing of particles, and even dry scenarios could capture a fraction, albeit smaller, of the particles entering the secondary side. The VTT tests showed that resuspension is important in aerosol retention within horizontal tubes and is enhanced by sudden velocity changes. All the available resuspension models are being assessed by comparison to data (new VTT results, EC/JRC Ispra STORM) and with each other, while the new VTT data will be used to develop a new empirical model. Revolatilisation tests in the small-scale REVAP facility (JRC/ITU) on PHEBUS FP samples show that Cs revaporisation can be very high (~95%) on flat metallic substrates. CsOH deposits on stainless steel have the same behaviour as that of the PHEBUS FP deposits. VTT are starting new tests on speciation from revaporisation aerosols complementary to the CHIP programme mentioned above.

### Session 5: Conclusions and Perspectives. Paper 5-2

Retention of aerosols in containment cracks can be effective, particularly in the presence of steam (SIMIBE tests, IRSN). Stand-alone and in-code models have been developed. They will be tested against data from experiments in COLIMA (CEA) to be performed under the PLINIUS platform; the successful proposal for which was coordinated within the Source Term area. A SARNET team is providing pre-test support.

The facilities involved in Containment Chemistry are PHEBUS FP, CAIMAN, SISYPHE, the Chalmers facility, PARIS and EPICUR [7], with data recently released from RTF P9T3 (AECL). The Iodine Data Book compiled by Waste Management Technology provides a critical review of chemistry data and models. CAIMAN results showed that in the presence of paints, irradiation and high temperature, organic iodide can be the dominant form of volatile iodine; in alkaline conditions, gaseous iodine concentrations decrease by several orders of magnitude. Mass transfer between sump and gas phase was addressed in SISYPHE; evaporating conditions increase the transfer rate from the liquid to the gas phase and change the steady-state iodine concentrations, the sump iodine concentration being reduced. The well-known two-film model was extended to these conditions, with improvements introduced into ASTEC. A more mechanistic model is now under validation [8].

The effect of radiation on the containment atmosphere and the effect of metallic impurities in the sump were investigated in the PARIS and Chalmers experimental programmes, respectively, while Chalmers/VTT are investigating speciation of iodine oxides/nitroxides formed in the atmosphere under radiolysis. The organic iodine formation models consider thermal and radiolytic mechanisms in the gas and liquid phases. There are however discrepancies in the aqueous modelling, essentially concerning the organic sources. Data from EPICUR are being interpreted using codes like ASTEC/IODE, INSPECT and LIRIC. Ruthenium behaviour in-containment has been studied experimentally and theoretically by IRSN (further EPICUR tests) and by Chalmers, as well as the effect of fission product heating on passive autocatalytic recombiners, where ASTEC/SOPHAEROS has successfully modelled the bench-scale RECI tests (IRSN); scaling effects are now being considered. Finally, cooperative evaluation with several codes of the ThAI-Iod9 integral test on containment iodine chemistry was completed under the coordination of GRS.

#### ***B.2.4 Integration of Research Activities***

From the above paragraphs, we can note that a real integration of these research activities has been achieved thanks to:

- Collaborations on pre and post calculations of experiments: for instance PSI performed pre and post-test calculations of the FZK QUENCH tests,
- Joint realization of experiments: for instance experimentalists from VTT have installed and operates specific instrumentation on the IRSN CHIP experiments,
- Joint definition and interpretation of experiments (many “interpretation circles” created and really active),
- Benchmarking of codes,
- Distribution of codes to partners in order to achieve a common understanding of experimental phenomena (ASTEC modules),
- Exchanges on the application of R&D results to the reactor scale,
- Round-robin exercise on EDX analyses of a prototypic corium sample by three laboratories (Cadarache, France; Karlsruhe, Germany; Rez, Czech Republic),
- Yearly technical meetings in each of the three topical areas (corium behaviour, containment integrity and source term), complemented by a large number of specialists’ meetings.

### B.3 Spreading of Excellence Activities

The third major type of activity concerns spreading of excellence. The more experienced organizations started to disseminate the excellence by preparing an educational course on SA phenomenology addressing PhD students and young researchers, given in January 2006 over 5 days. A training course on “Accident progression (data, analysis and uncertainties)”, addressing instead more experienced nuclear safety specialists, was given in March 2007 over 5 days. Finally, a third course was organized in Budapest in April 2008 covering both phenomenology and severe accident scenario codes. From 40 to 100 persons attended to each of these courses.

Besides this, a textbook on SA phenomenology is being written. It is now practically completed and will be edited in 2009. This covers historical aspects of Light Water Reactor safety and principles, phenomena concerning in-vessel accident progression, both early and late containment failure, fission product release and transport; it contains a description of analysis tools or codes, of management and termination of SA, as well as environmental management. It also gives elements on Generation 3 Reactors. The partners who agreed to work together in preparing these courses and writing this book are universities, TSOs, national laboratories and industrial organizations that share their talent and experience within SARNET.

A mobility programme, under which students and researchers can go into different laboratories of SARNET for training, complements these spreading of excellence activities. 33 mobilities, with an average duration of 3 months, have been funded by SARNET.

Three conferences (European Review Meetings on Severe Accident Research – ERMSAR) have been organized in France, Germany and Bulgaria as a forum to the Severe Accident community. They are becoming one of the major events in the world on this topic.

Finally, about 300 SARNET papers in Conferences and/or in Journals can be counted. A complete list will be provided in the final (public) synthesis report of SARNET.

### C. CONCLUSION

The SARNET Network of Excellence activities started in April 2004 with the ambitious but highly important objective to provide an appropriate frame for achieving a sustainable integration of the European severe accident research capacities.

By capitalizing the acquired knowledge in the ASTEC code and in the DATANET database of experimental results, SARNET is producing conditions necessary for preserving the knowledge produced by thousands of person-years of research, and disseminating it to a large number of end-users. The ASTEC code is being actively used as well as DATANET.

By fostering collaborative work in the PSA2 domain, SARNET has started to create the necessary conditions for harmonizing the approaches and making Europe a leader in SA computer code and risk assessment methodology.

Through an education and training programme (organization of courses, writing a text book addressing young scientists), SARNET is developing synergies with educational institutions to keep attractive this domain of activity for young people. This is reinforced by an efficient mobility programme, which allows fruitful exchanges between European laboratories for young students and researchers.

**Session 5: Conclusions and Perspectives. Paper 5-2**

By fostering collaborative R&D work in the domains of corium behaviour, containment integrity and source term, SARNET is progressing to solve remaining outstanding issues and to provide ASTEC with modelling recommendations. Proposals have been elaborated for various ASTEC models and their implementation is either done or under way.

SARNET is clearly becoming a reference, in terms of research priorities in the field of SA, having impact on national programmes and associated budgets. Progressively all the research activities in this field will become coordinated by the Network, which contributes to an optimised use of European resources.

Finally, a SARNET follow-up is in its final negotiation phase with the EC for an additional four year duration, then SARNET will really become a self-sustainable entity [9].

**ACKNOWLEDGMENTS**

Special thanks are given to the SARNET Work-Package and Sub-Work-Package leaders: M. Steinbrück (FZK), G. Repetto (IRSN), C. Duriez (IRSN), W. M. Ma (KTH), V. Koundy (IRSN), M. Bürger (IKE), B. Spindler (CEA), H. Wilkening (JRC/IE), I. Kljenak (JSI), D. Magallon (CEA), P. Giordano (IRSN), L. Herranz (CIEMAT). They have been the key links from the Management Team to all the technical contributors within SARNET organizations, too numerous to name, but to whom the authors are also very grateful. Last but not least, the authors thank the European Commission and its representative - M. Hugon who showed a really strong interest in the Network - for funding SARNET, in the 6<sup>th</sup> FP, area “Nuclear Fission: Safety of Existing Nuclear Installations”, under contract number FI6O-CT-2004-509065.

**REFERENCES**

- [1] D. Magallon et al., “European Expert Network for the Reduction of Uncertainties in Severe Accident Safety Issues (EURSAFE)”, Nuclear Engineering and Design, vol. 235, pp. 309-346 (2005).
- [2] J.-C. Micaelli et al., “SARNET: A European Cooperative Effort on LWR Severe Accident Research”, Proc. European Nuclear Conference, Versailles, France (2005).
- [3] J.-P. Van Dorsselaere, H.-J. Allelein and K. Neu, “Progress and Perspectives of ASTEC Applications in the European Network SARNET”, Proc. EUROSARE Forum, Paris, France (2006).
- [4] C. Journeau et al., “European Research on the Corium Issues within the SARNET Network of Excellence”, Proc. Int. Congress on Advances in Nuclear Power Plants (ICAPP '08), Anaheim, California, USA (2008).
- [5] M. Buck et al., “Status of FCI Modeling and Reactor Applications: Achievements during the SARNET Project”, European Review Meeting on Severe Accident Research (ERMSAR 2008), Nesseber, Bulgaria (2008).

**Session 5: Conclusions and Perspectives. Paper 5-2**

- [6] T. Haste et al., “SARNET: Integrating Severe Accident Research in Europe: Key Issues in the Source Term Area”, Proc. Int. Congress on Advances in Nuclear Power Plants (ICAPP '06), Reno, Nevada, USA (2006).
- [7] B. Clément and R. Zeyen, “The Phébus FP and International Source Term Programmes”, Proc. Int. Conf. on Nuclear Energy for New Europe, Bled, Slovenia (2005).
- [8] L. E. Herranz, J. Fontanet and L. Cantrel, “Impact of Evaporative Conditions on Iodine Mass Transfer during Severe Accidents”, 12<sup>th</sup> Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-12), Pittsburgh, Pennsylvania, USA (2007).
- [9] T. Albiol et al., “Presentation of SARNET2”, European Review Meeting on Severe Accident Research (ERMSAR 2008), Nesseber, Bulgaria (2008).