Session 1. Opening and overview – Paper n°S1-2

Evaluation of Research Priorities in the Frame of SARNET

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Abstract

The objectives of SARNET are to define common research programmes in the field of severe accidents and to develop common computer tools and methodologies for safety assessment in this field. To reach these objectives several elements or work programmes (WP) are established. One of these work packages is the WP 'Severe Accident Research Priorities' (SARP) with the aim to review and reassess the priorities of research issues as basis to harmonize and to re-orient research programmes, to define new ones, and to close – if possible - resolved issues on a common basis. This action will make use notably of (1) the outcome of the EURSAFE actions, i.e., the results of the Phenomena Identification and Ranking Tables (PIRT) on severe accidents, (2) the results of the qualification and benchmarking activities on ASTEC, (3) the results of reactor calculations carried out in the other activities, and (4) the outcome of the research performed in the three thematic sub domains of SARNET (corium, containment and source term).

The main outcome of EURSAFE was a list of 21 topics (see table 1), which includes recommendations for experimental programmes and code developments and forms the basis of the work of the SARP. Also the methodology applied in EURSAFE to consider both risk potential and the severe accident issues, where large uncertainties still subsist, were adopted. The analyses of the progress of research and developmental activities are performed in close cooperation with the management team and the coordinators of the WPs. These analyses will consider whether (1) any research issue is resolved due to reduction of uncertainties or gain of scientific insights, (2) any new issue has to be added to the list of needed research, (3) any new process or phenomenon has to be included in the general PIRT list taking into account the safety relevance and lack of knowledge, and whether (4) any new accident management programme has to be developed to cope with unresolved problems. Furthermore a strategy plan will be elaborated to ensure a wide consensus with end user requirements and the objectives of SARNET research activities.

A Introduction

The objectives and the work scope of SARNET were comprehensively described in [6]. The SARNET work program is based on the results of EURSAFE [4], which was a thematic network with duration of two years starting 1st December 2001 and finishing 31st November 2003. The main outcome of EURSAFE was a list of 21 areas of needed research in the domain of severe accidents, which includes recommendations for experimental programmes and code development. To further develop this list as a living document the work package "Severe Accident Research Priorities (SARP)" was established.

This presentation describes

- The objectives and the work scope of the work package SARP.
- The methodology applied in EURSAFE to establish an internationally agreed list of needed research items. (PIRT table)
- The strategy which is followed to fulfil the objectives of the work package.
- Main results of work performed.

The activities in SARP should focus on the main results of SARNET and out of this the identification of items, where the knowledge has been considerably improved and further experimental research and/or model development (R&D) seems not to be of high priority. Furthermore it should identify research areas which need reorientation to fulfil the objectives of the work package and last but not least the identification of needed research not yet being covered by the SARNET work program. The outcome of the SARP work should be an updated ranking, giving different priorities to the research issues. This shall help the decision making on performing the different research programmes.

B Objectives and work scope of the work package SARP

The objectives of SARP are defined as:

To provide the Governing Board of SARNET with guidelines for defining the orientations to be given to the Joint Programme Activities (JPA) in terms of joint activities for research of common interest and high priority. This includes reassessment the priorities for research to be performed in the field of severe accident phenomena and management, notably using the results of EURSAFE, the ASTEC work packages, and the Level 2 PSA work package.

The working scope as outlined in the "Description of Work" is:

- Agree on methodology.
- Identify issues resulting from EURSAFE not appropriately covered by SARNET and review
- Analyse research and development progress and results from Level 2 PSA studies.
- Reassess the ranking of research issues and reorient the priorities.
- Review potential experimental and theoretical programmes to address these issues.
- Make recommendations for research and development programme revision

The following chapters will illustrate the working methods studied to find an effective way how to fulfil the requirements and how to perform the work expected from the SARP team.

C EURSAFE methodology and results

The objectives of the EURSAFE thematic network (Ref. [1]) were to establish a large consensus on the Severe Accident issues, where large uncertainties still subsist, and to propose a structure to address these uncertainties by appropriate R&D programmes making the best use of the European resources. It incorporated issues related to existing plants (PWR, BWR and VVER), lifetime extension of these plants, evolutionary concepts (higher burn-up and MOX fuels), and safety and efficiency of future systems.

Twenty partners representing R&D governmental institutions, regulatory bodies, nuclear industry, utilities and universities from 9 European countries (Finland, France, Germany, Spain, Sweden, United Kingdom, Czech Republic, Hungary, Switzerland) and Canada were brought to work together in a network structure, which was supposed to be a starting point of SARNET.

To achieve the objectives, sufficient convergence on issues and phenomena and on their importance in terms of safety and knowledge was required among all the major European actors in Nuclear Safety. The final objective was a consensual approach to resolve the remaining uncertainties and open issues. Establishing Phenomena Identification and Ranking Tables (PIRT) has been proved in other areas (e.g. Loss-of-coolant accidents, LOCA) to be an efficient and unbiased way to reach such a consensus (Ref. [2]).

In EURSAFE the first PIRT was realised for severe accidents as an initial step towards the objectives. It integrated all the severe accident issues from core degradation up to release of fission products from the containment, taking into account any possible counter-measures and the evolution of fuel management.

As a basis for the PIRT, a comprehensive list of 1016 severe accident phenomena was established (see Ref. [3]). The phenomena were classified in five groups:

- In-vessel (162 phenomena),
- Ex-vessel (149 phenomena),
- Dynamic loading (461 phenomena),
- Long term loading (116 phenomena),
- Fission products (128 phenomena).

Three safety-oriented groups of experts scrutinized these phenomena of the five lists and ranked them in accordance to their safety importance for

- Primary circuit,
- Containment and
- Source term.

The rationale for voting on safety importance was as follows:

- **Vote level 3:** High priority; the phenomenon (or the aspect) is highly important for safety and the probability of occurrence is high, medium or unknown. The uncertainties on this phenomenon should be reduced to the minimum possible.
- **Vote level 3L:** High priority but low probability; the phenomenon (or the aspect) has important consequences and the probability of occurrence is low.
- **Vote level 2:** Medium priority; the phenomenon (or the aspect) is important for safety and the probability of occurrence is medium or unknown.
- **Vote level 1:** Low priority; the phenomenon (or the aspect) has low importance for safety, or has medium importance for safety and its probability of occurrence is low.

- **Vote NO:** No Opinion.
- **Vote NA:** Not Applicable; phenomenon not relevant for the considered safety oriented situation.
- **"-":** No participation.

According to the number of High, Medium and Low priority votes assigned to a phenomenon, an Importance Ratio (IR) was deduced [6].

Any phenomenon, for which the number of votes was less than five, whatever was the average value of the votes, was disregarded. On the other hand, phenomena having more than five votes "3" were selected as highly important anyway. A few bi-modal cases (phenomena having an equal number of votes 1 and 3) could not be resolved and remained in the list.

After this evaluation a reduced list of 239 severe accident phenomena with high importance for reactor safety was established (see Ref. [3])

Then, the five previously mentioned phenomena-oriented groups ranked the phenomena, selected as important for safety in terms of knowledge. Rationale for voting on phenomena knowledge was as follows:

- **Vote level 3:** The phenomenon/aspect is only partly understood. The models are rudimentary. The model verification is insufficient due to a significant lack of experimental data. Needs significant R&D effort.
- **Vote level 2:** The phenomenon/aspect is on the whole understood, uncertainties remain for unexplored parameter ranges or extrapolation to reactor scale. The main processes are described by adequate models but the verification is not complete due to a limited understanding and to limited number of data.
- **Vote level 1:** The phenomenon/aspect is well understood. The processes are adequately modelled and well verified in general on an extended experimental basis. Needs little or no R&D.
- **Vote NF:** None of the suggested votes fits; provide explanation in the comments.
- **Vote NE:** Problem unknown (no expertise)
- **"–":** no participation

The vote averaging for the Knowledge Ratio (KR) was performed in the same way like for the Importance Ratio (IR). [6]

After completion of the two ranking phases, this procedure clearly emphasized the phenomena being simultaneously highly important for safety and significantly lacking of knowledge. The remaining 106 phenomena were obviously candidates for further R&D work, which was specified in the PIRT's implications work package (see Ref. [3]). The allocation of these phenomena to the specified domains was the following:

- 24 phenomena for In-vessel,
- 28 phenomena for Ex-vessel,
- 26 phenomena for Dynamic loading,
- 10 phenomena for Long term loading,
- 18 phenomena for Fission products.

Starting with 1016 identified phenomena, the list was reduced to 239 important for safety, of which 106 were found with significant lack of knowledge. The list was in turn divided into two categories: phenomena with most significant lack of knowledge (57 phenomena) and those with a significant lack of knowledge for some aspects (49 phenomena).

After that the PIRT implications were deduced taking into account existing and planned European facilities, codes and programmes. The work package included:

- Defining R&D needs in terms of objectives and priorities;
- Identifying the required R&D tasks in terms of experimental programmes and codes;
- Reviewing the European facilities and codes which could be used for these tasks, taking into account the existing and planned programmes.

As a further step, the research needs to address each selected phenomenon of the PIRT list were identified. First, the objectives of research and the description of programmes and codes needed (including existing capabilities) to address each selected phenomena of the PIRT list were reviewed. A list was established assigning to each selected phenomenon the related research needs and programmes (Ref. [4], Ref. [5]).

According to the similarities in terms of research needs and physical processes, with the scope of being able to set up a limited number of coherent R&D programmes, several phenomena were merged to research issues without further elimination or selection. A rationale for these research needs was established based on safety relevance and lack of knowledge. The outcome of this process is summarised in Table 1, which gives the 21 items of needed research (EURSAFE Research Issues ERI) and corresponding rationales drawn from the 106 phenomena selected in the PIRT.

Table 1: EURSAFE Research Issue and Rationale for Selection

ERI	EURSAFE Research Issue	Rationale for selection
1,1	Hydrogen generation during re-flooding or melt relocation into water	Rapid generation of hydrogen which may not be accommodated by re-combiners and the risk of early containment failure. Improve knowledge about the magnitude of hydrogen generation.
1,2	Core coolability during re-flooding and thermal-hydraulics within particulate debris	Termination of the accident by re-flooding of the core while maintaining RCS integrity. Increase predictability of core cooling during re-flooding.
1,3	Corium coolability in lower head and external corium catcher device	Improve predictability of the thermal loading on RPV lower head or corium catcher devices to maintain their integrity.
1,4	Integrity of RPV due to external vessel cooling	Improve data base for critical heat flux and external cooling conditions to evaluate and design AM strategies of external vessel cooling for in-vessel melt retention.
1,5	Integrity of RCS	Improve predictability of heat distribution in the RCS to quantify the risk of RCS failure and possible containment bypass.
1,6	Corium release following vessel failure	Improve predictability of mode and location of RPV failure to characterise the corium release into the containment.
2,1	MCCI: molten pool configuration and concrete ablation	Improve predictability of axial versus radial ablation up to late phase MCCI to determine basement material failure time and loss of containment integrity.
2,2	Ex-Vessel corium coolability, top flooding	Increase the knowledge of cooling mechanisms by top flooding the corium pool to demonstrate termination of accident progression and maintenance of containment integrity.
2,3	Ex-Vessel corium catcher: corium ceramics interaction and properties	Demonstrate the efficiency of specific corium catcher designs by improving the predictability of the corium interaction with corium catcher materials.
2,4	Ex-Vessel corium catcher: coolability and water bottom injection	Demonstrate the efficiency of water bottom injection to cool corium pool and its impact on containment pressurisation.
3,1	Melt relocation into water and particulate formation	Determine characteristics of jet fragmentation, debris bed formation and debris coolability towards maintenance of vessel and respectively containment integrity.
3,2	FCI incl. steam explosion: melt into water, in-vessel and ex-vessel	Increase the knowledge of parameters affecting steam explosion energetic during corium relocation into water and determine the risk of vessel or containment failure.
3,3	FCI incl. steam explosion in stratified situation	Investigate the risk of weakened vessel failure during re-flooding of a molten pool in the lower head.
3,4	Containment atmosphere mixing and hydrogen combustion / detonation	Identify the risk of early containment failure due to hydrogen accumulation leading to deflagration / detonation and to identify counter-measures.
3,5	Dynamic and static behaviour of containment, crack formation and leakage at penetrations	Estimate the leakage of fission products to the environment.
4,1	Direct containment heating	Increase the knowledge of parameters affecting the pressure build-up due to DCH and determine the risk of containment failure.
5,1	Oxidising environment impact on source term	Quantify the source term, in particular for Ru, under oxidation conditions / air ingress for HBU and MOX.
5,2	RCS high temperature chemistry impact on source term	Improve predictability of iodine species exiting RCS to provide the best estimate of the source into the containment.
5,3	Aerosol behaviour impact on source term	Quantify the source term for aerosol retention in the secondary side of steam generator and leakage through cracks in the containment wall as well as the source into the containment due to re-volatilization in RCS.
5,4	Containment chemistry impact on source term	Improve the predictability of iodine chemistry in the containment to reduce the uncertainty in iodine source term.
5,5	Core re-flooding impact on source term	Characterise and quantify the FP release during core re-flooding.

D Decision Procedure followed in the work package SARP

The procedure for decision making applied in the work package SARP – based on the EURSAFE method - is outlined in the following and was discussed during ERMSAR 2005 in order to develop an agreed procedure. It should be mentioned, that this work requires a strong cooperation between SARP team, technical leaders of the work package, topical coordinators and the Management Team.

One requirement is that all steps of the decision process must be documented to allow a well funded judgement for the SARNET community and for the end users of SARNET products. For this reason a template (see ERMSAR 2005) was constructed, which will be described in the following. The structure of the template reflects the strategy of the intended decision process.

The template is used for the three possible “Decisions”:

1. The issue is closed by sufficiently improved knowledge (To be closed).
2. The work should be reoriented to fulfil the objectives (Reorientation).
3. A new research item should be set up (New Item).

Table 2: Template for decision process

<table>
<tr><td>Action</td><td>Decision
New Item</td><td>Topical Research Area
Source Term</td><td>Work Package Number
WP16</td><td>EURSAFE Research Issue
ERI 5,1 & 5,4</td><td>EURSAFE Ref. Number
ERN 5,1,026 & 5,5,000</td><td>YY/MM/DD
Date</td></tr>
<tr><td></td><td colspan="5">Short description of the action:
Investigate the volatility and behaviour of Ruthenium in the containment.</td><td>05/06/23</td></tr>
<tr><td rowspan="4">A</td><td colspan="3">Items for needed Research ERI 5,1
Oxidising environment impact on source term.</td><td colspan="2">Rationale for selection ERI 5,1
Quantify the source term, in particular for Ru, under oxidation conditions / air ingress for HBU and MOX.</td><td rowspan="4">05/10/23</td></tr>
<tr><td colspan="3">Items for needed Research ERI 5,4
Containment chemistry impact on source term.</td><td colspan="2">Rationale for selection ERI 5,4
Improve the predictability of iodine chemistry in the containment to reduce the uncertainty in iodine source term.</td></tr>
<tr><td colspan="5">Description of phenomena: Fission Products \ Invessel Release \ Release mechanisms for FPs and actinides from solid fuel \ ERN 5,1,026:
Important increase of the volatility of certain elements due to a high state of oxidation, e.g. in the situation of air ingress in the core.
Containment filtered pressure relief is a likely measure to achieve severe accident final safe state. The issue is important for assessing containment by-pass scenarios.
Knowledge base during refuelling outages, when the reactor vessel is open, should be increased. Chemistry in the containment is an important issue for long-term accident management.</td></tr>
<tr><td>SoV \ PC: 1.67
2x1 + 0x2 + 1x3</td><td>SoV \ Cont: 1.00
3x1 + 0x2 + 0x3</td><td>SoV \ ST: 2.36
3x1 + 3x2 + 8x3</td><td>PoV: 2.69
1x1 + 2x2 + 10x3</td><td>Selected List: 1</td></tr>
</table>

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<table>
<tr><td>Ac-
tion</td><td>Decision
New Item</td><td>Topical Research Area
Source Term</td><td>Work Package Number
WP16</td><td>EURSAFE Research Issue
ERI 5,1 & 5,4</td><td>EURSAFE Ref. Number
ERN 5,1,026 & 5,5,000</td><td>YY/MM/DD
Date</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Objectives of needed research:
B1: Review of existing data

B2: analysis of reactor scenarios to define the test conditions

A3: Small scale exp. to examine the speciation and aerosol behaviour of Ru under different oxidising environments, temperatures etc. with simulants and real FPs and other materials

B4: modelling improvement for FP release induced by fuel oxidation

B5: modelling effort for Ru transport including necessary kinetic effects
A6: integral exp. to complement existing data from separate effect tests - coupling between fuel degradation and FP release</td><td colspan="3">Description of Experimental Program / Codes:

ATHLET-CD, ASTEC

Transport (thermal gradient tube etc.) and speciation (mass spectrometry, UV/vis spectroscopy etc.) experiments would be conducted under a range of conditions relevant to severe reactor accidents with involve identification of the dominant vapour-phase and condensed-phase (aerosol) species of ruthenium and simulant FPs.
RUSET, (AEKI): separate effect tests on the oxidation and release of Ru and other simulant FPs (1 rod segment)
VERDON, MADRAGUE, real FP materials
CODEX-RU bundle (7-9 rods) tests with fission product simulant materials.

ICARE/ELSA, DIVA/ELSA (ASTEC)

SOPHAEROS (ASTEC)

PHEBUS 2K planned mid 2007</td><td rowspan="2"></td></tr>
<tr><td colspan="5">Description of phenomena: Fission Products \ Iodine Chemistry \ ERN 5,5,000:
There is no specific element besides Iodine included in this chapter.</td></tr>
<tr><td>B</td><td colspan="5">Rationale for the decision to be taken, written by technical leader of the work package:
(to be completed)</td><td></td></tr>
<tr><td>C</td><td colspan="5">Evaluation of rationale by the topical coordinator (State of knowledge, test facility, model development):
(to be completed)</td><td></td></tr>
<tr><td rowspan="2">D</td><td colspan="5">Assessment of rationale by the SARP team (Safety and risk significance, review evaluation by TC):
(to be completed)</td><td rowspan="2"></td></tr>
<tr><td>SoV \ PC: 0.00
0x1 + 0x2 + 0x3</td><td>SoV \ Cont: 0.00
0x1 + 0x2 + 0x3</td><td>SoV \ ST: 0.00
0x1 + 0x2 + 0x3</td><td>PoV: 0.00
0x1 + 0x2 + 0x3</td><td>Selected List: 0</td></tr>
<tr><td>E</td><td colspan="5">Review of SARP evaluation by MT:
(to be completed)</td><td></td></tr>
<tr><td>F</td><td colspan="5">Statement of decision to be published on the ACT and to be given to end users for comment:
(to be completed)</td><td></td></tr>
<tr><td>G</td><td colspan="5">Comments from the SARNET community and end user:
(to be completed)</td><td></td></tr>
<tr><td>H</td><td colspan="5">Summary of comments from the end user compiled by SARP team:
(to be completed)</td><td></td></tr>
<tr><td>I</td><td colspan="5">Revised statement of decision to be published on the ACT:
(to be completed)</td><td></td></tr>
<tr><td>J</td><td colspan="2">Objectives of needed research for the new item:
(to be completed)</td><td colspan="3">Description of Experimental Program / Codes:
(to be completed)</td><td></td></tr>
</table>

The corresponding indication of the three possible decisions is the first entry in the head line. It includes with the "Topical Research Area", the "Work Package Number" as well as the corresponding “EURSAFE Research Issue” and “EURSAFE Reference Number” the main indicators. A “Short description of the action” is given by the technical leader who requested the decision.

After this descriptive part, the template includes 10 “Actions” named “A” to “J” with a clear indication of responsibility and the time of execution “Date”.

The first action “A” is to reflect the situation described by EURSAFE. It has to be filled in by the technical leaders of the work package and the SARP. It comprises

- the description of the corresponding “EURSAFE Research Issue” (Table 1), “Rationale for selection” and the “Description of phenomena” (see Ref. [3]),
- the Safety oriented Votes (SoV) regarding the Primary Circuit (PC), Containment (Cont) and Source Term (ST) as well as the Phenomenon oriented Vote (PoV) and the selection of priority list (1 = highest, 2 = second, 0 = not selected) (see Ref. [3]),
- the “Objectives of needed research” and “Description of experimental program and code development” (see Ref. [5]).

The second action “B” is a comprehensive description of the “Rationale for the decision to be taken, written by the technical leader of the work package”. If the decision process is launched by the SARP, its technical leader takes this action.

The following step “C” is the “Evaluation of rationale by the topical coordinator”. With this the rationale written by the technical leader is revised and the state of knowledge, the corresponding test facilities and computer programmes, modules or models are described and listed.

After this the SARP team has to asses in step “D” the rationale and justifications of the leaders of the work package. Furthermore it has, in accordance to the methodology developed in EURSAFE, to vote regarding the safety relevance and risk potential (SoV \ PC, Cont, ST) as well as to estimate the state of knowledge (PoV).

In the next step “E” the management team (MT) should review the evaluation of the SARP and informs all previous actors about its assessment to allow them to clarify or to improve the arguments documented in the template.

In step “F” the preliminary decision is to be published in the ACT and distributed to the end users by the MT with reference to the template and a clear dead line for comments.

The following three steps should allow the community to comment on the development of the research issues, but it should not delay the decision making process. All comments of the SARNET community and the end users are collected and documented (step “G”). Then the SARP team compiles the comments and briefly summarizes them (step “H”). If necessary, the decision is revised in cooperation of SARP and MT (step “I”) and published as final decision in the ACT.

In the case of a new or a newly re-oriented research item, the “Objectives of needed research for the new item” and the “Description of experimental program or code development” are documented in step “J” by applying the same methodology as utilised in EURSAFE. In case of the decision to close the issue, this article is not applicable.

In parallel with these actions, the tables describing the phenomena (Ref. [3]), the objectives of research (Ref. [5]), and the issues of needed research (Table 1) are updated as a living document. This strategy is an attempt to come within a reasonable time with consideration of all pertinent factors to an agreed decision considering all aspects of innovation and economic efficiency.

The extensive review and assessment work of the SARP group in the last year was only sparely commented according to this procedure; therefore it is questionable whether this procedure of commenting and feed back on the SARP work and results should be carried on in such an intensive way as outlined.

E Summary of results of the SARP work package

The methodology applied in EURSAFE to establish an internationally agreed list of needed research items was proven as adequate. It started with a comprehensive list of phenomena and finished by using a bottom-up approach with 21 items of needed research areas. Investigations showed that a well balanced top-down approach gives very similar results. Therefore the EURSAFE methodology has been applied in SARNET too.

Up to know seven possible new or reoriented research items were identified. The assessment of these items was performed. The following items were addressed:

- Investigation of HBU cladding materials at high temperature and under reflood conditions,
- Spreading of corium into nearby compartments possibly filled with water
- Effect of hydrogen mitigation systems (esp. PAR) on H2 distribution
- Combustion of H2 jets in atmosphere with different H2 concentration (in relation to DCH)
- Retention of aerosol in RCS, SGT or concrete cracks under consideration of mechanical resuspension
- Decomposition of iodides by heat-up in PARs and its impact on source term
- Ruthenium volatility and behaviour in containment

Only for the issue of the decomposition of iodides in PARs additional tests and calculations were proposed. Other items could be covered by a reorientation or small extension of experimental and/or analytical work in the work steps of the SARNET work packages; some did not even justify additional R&D effort.

In the last SARP meeting, held at FZK Karlsruhe on February 28th 2007, all ERI issues from table 1 were reassessed in a top down approach with respect to further necessary activities in SARNET as proposal for the Management Team and the Governing Board.

According to the SARP discussion the expression ‘issue to be regarded as closed’ means, that for the issue the current knowledge is considered as sufficient assessing both the state and progress of knowledge and the risk and safety relevance and taking into account ongoing activities.

The ERI 1.1 issue concerns the in-vessel H2 generation with metal rich melt mixtures during reflood and during melt relocation into water of lower head. The first part was assessed with priority 1, the second part with 2 in EURSAFE. However PSA results assess reflooding as very plant specific, because where shall the water for reflood come from when it was not available earlier leading to core melt. During reflood hydrogen is generated rapidly , which may not be recombined by recombiners and increase the risk of early containment failure. The uncertainties on the magnitude of the H2 generation rates are too large. An improvement of knowledge is needed. The item H2 generation during reflood is treated in WP 9-1 in the Quench tests 11, 12, 13 and the PARAMETER SF tests in the ISTC program. It will be extended to new cladding material in the coming JPA4. For H2 generation during melt relocation into water like with corium jets etc. the only data available are from FARO. In WP10 and WP11 it will be investigated analytically. Although it has high risk significance, it was given a **medium priority**, because research is only needed for confirmation and validation of models. The fundamental knowledge is available.

The ERI 1,2 and 1,3a issues concern the core and debris coolability (rod failure, molten pool formation, molten pool and debris cooling, crust failure) and thermal-hydraulics within particulate debris during reflood. Because ERI 1,3a, the corium coolability in lower head (the in-vessel aspect of ERI 1,3) is strongly related to ERI 1,2, they were combined. These research items assigned to ERI 1,3a, clearly address the details of the phenomena to be investigated for in-vessel melt pool behaviour. Although from PSA study reflooding is classified with low probability (see arguments above), the issue was ranked **high,** because a reflooding of the core can terminate an accident and corresponding severe accident management measures are intended, investigation of reflooding is important. The items are treated in WP11-1 with small scale experiments DEFOR, STYX, DEBRIS-KTH, INCO_KTH, POMEGON, but tests in larger scale on coolability in representative conditions would be very interesting and would increase the necessary knowledge significantly. Late phase core degradation and corium behaviour in lower head are treated in WP10-1. What is missing are activities for spatial growth of melt pool and crust failure in the core region and related characteristics of corium arrival in residual water and spatial growth of melt pool in lower head.

In-vessel melt retention aspects and the improvement of the predictability of the thermal loading is mainly a matter of high interest for BWR and reactors with low power density (for WWER 440 solved). For large western Europe PWRs there is no way regarded possible to keep the melt in the vessel. Therefore it is classified with low priority for PWRs. The in-vessel melt retention aspects should be treated in conjunction with the external RPV cooling (ERI 1,4).

ERI 1,3b issue concerns the unique item corium coolability in external corium catcher. The predictability of the thermal loading on the core catcher device needs further improvement. The heat transfer at the corium pool boundaries is unclear. The issue was treated in WP 11-3 for the EPR concept and was experimentally closed. For future reactors it is out of scope of SARNET and to be investigated by the industry. It was already of second priority and was ranked of **low** interest.

ERI 1,4 issue concerns the unique item keeping the RPV integrity by external vessel cooling. The data base for critical heat flux and external cooling conditions needs to be improved in order to evaluate and design AM measures for external vessel cooling for in-vessel melt retention. This possibility for AM depends on the local conditions in each plant. For large PWR it is regarded as not to be successful. For WWER 440 external vessel cooling has been successfully proven, but for BWR it needs further investigation. Especially the influence of BWR lower head penetrations on melt cooling and its influence on the external convection should be examined. The issue is treated in WP10-2 under vessel failure and corium release into cavity. It should be treated in conjunction with ERI 1,3a (melt pool coolability in LH). Due to the importance for BWRs it was classified with **medium** priority.

ERI 1,5 issue concerns the integrity of the reactor coolant system (RCS). It reflects on the predictability of the heat distribution in the RCS, especially in the SGs, to quantify the risk of RCS failure and possible containment bypass. The effect of high thermo mechanical loads on SG tubes is still a point of investigations. In SARNET no experimental program exists for this item. It is only important for SGT failure and the following containment bypass, which can be coped with by the AM measure flooding of the SG. From PSA results this is only relevant for high/medium pressure scenarios and then also for hot leg and surge line. The main uncertainties come from the core degradation dynamics with its Zr oxidation as major heat source. Therefore the issue, already ranked as second priority**, could be closed**. Another aspect is the failure of the RCS pipes due to high temperatures under high pressure scenarios. In principle high pressure scenarios should be prevented by depressurisation of the primary circuit. But if this fails, PSA results and analysis indicate a failure of the RCS due to high temperature and depressurisation occurs. But this is again second order behind the AM measure.

ERI 1,6 issue concerns the corium release from the failed vessel. The predictability of the failure mode and the location of failure of the RPV to characterise the corium release into the cavity/containment should be improved. The information on the break location is regarded as sufficient, but there is no solution for the prediction of the break size. Due to the hole ablation during the outflow this lack of knowledge is regarded as not significant, although the initial hole size is a significant starting condition for possible DCH (see ERI 4,1). This issue and its aspects are treated in WP 10-2 with the OLHF-1 benchmark and with the interpretation of FOREVER experiments. Links exist with the ISTC projects INVECOR (in-vessel corium retention) and METCOR-P (corium melt interaction with NPP pressure vessel steel). Therefore the issue, already ranked as second priority, should not be investigated with high priority and could be **closed** for further intensive research in the near future.

ERI 2,1 issue concerns the ex-vessel melt pool configuration in the cavity during the MCCI process and the concrete ablation, which affect the containment integrity.

ERI 2,2 issue – to be treated together with ERI 2,1 - concerns the ex-vessel corium coolability in the cavity by top flooding and all the encountered phenomena dealing with heat transfer, crust formation, sparging gas and cracking of crust. These issues were put together for combined treatment in the research, because the phenomena of both issues are coupled. The MCCI is treated in WP11-2 with first priority on the investigation of layer configuration and layer stability under sparging gas; with second priority heat transfer and convection in the melt pool.

Recent work indicated that the radial versus axial ablation is generally underpredicted. Considering the new experimental findings and the high risk significance to determine the basemat failure, it is recognized, that the MCCI and its radial/axial corium erosion is not modelled adequately und large uncertainties subsist, especially for the late phase of MCCI. Although radial melt spreading under sump water next to the cavity is plant design specific, the preceding radial erosion and the distribution of the energy between radial and axial erosion during the melting process influences strongly the prediction of a possible basemat failure.

Further on the knowledge on the cooling mechanisms by top flooding of the ex-vessel corium pool needs to be increased, because it influences significantly the calculated results, if the basemat erosion stops or not, which affects the containment integrity. The uncertainties are large. The corium coolability by top flooding is investigated in WP11-3 with first priority on the heat transfer between the upper crust and the water on top. Due to the risk significance the combined issues were classified with **high priority**, although PSAs for different plants result in different importance ranking.

ERI 2,3 issue concerns the ex-vessel corium catcher and its related phenomena concerning interaction of corium and ceramics.

ERI 2,4 issue concerns the corium coolability by bottom water injection in the catcher. These items might affect the containment integrity. Both aspects were treated in WP11-2 and 11-3. The efficiencies of different corium catcher designs and the efficiency of water bottom injection were demonstrated. Further investigations for plant specific geometrical conditions can be performed by the industry. Some analytical efforts should be continued to keep the knowledge for generation III and IV plants. Both issues were regarded as **closed**.

ERI 3,1 issue concerns the melt relocation into water in the lower head and consequent particulate formation.

ERI 3,2 issue concerns fuel coolant interaction (FCI) including steam explosion in the ex-vessel phase, in case water is in the cavity. These two issues are related to each other: the melt relocation into water determines the boundary conditions for a possible steam explosion. In-vessel steam explosion is no longer regarded as a significant threat.

The investigations performed in WP13-1 FCI are aiming at the characteristics of jet fragmentation, debris bed formation and debris coolability and to increase the knowledge of parameters affecting the steam explosion energetic during corium relocation into water in order to determine better the risk of containment failure. Different experimental facilities like KROTOS, TROI, MISTE, DEFOR are available; the SERENA OECD working group covers this area.. The ongoing programs are expected to improve the predictive capability of the FCI codes to a sufficient level for steam explosion risk assessment and management. The fragmentation and dynamic loading by FCI, the energy conversion, propagation and jet break up in deep pools are regarded of 1. priority.

Due to the high risk significance for the containment integrity the issue is classified with **high priority** in the SARNET frame. Some answers are expected from the related OECD projects and more analytical efforts with better models are needed for the transmission of the experimental results to plant conditions and the plant application. The ex-vessel findings should be transferred to the in-vessel situation, because most phenomena are expected to be similar for in-vessel and ex-vessel situation.

ERI 3,3 issue concerns FCI including a possible steam explosion in a weakened vessel during reflooding of a molten pool in lower head. On the basis of available experimental results the probability for a high energetic in-vessel steam explosion is very low, therefore the issue was discussed to be regarded as **closed.**

ERI 3,4 issue concerns the mixing of hydrogen in the containment atmosphere, possible hydrogen combustion/detonation processes and the influence of countermeasures like recombiners or effect of spray system. The items flame acceleration aspects, the produced pressure loads and ignition by recombiners are treated in WP12-1 and 12-2, especially ignition by recombiners and the scaling effect for accelerated flames are points of increased interest. Especially analytical activities are necessary to improve the predictability of the codes (mainly CFD codes) to simulate hydrogen combustion. DDT is not treated in SARNET WPs.

Due to hydrogen accumulation and possible overload of recombiners installed as a countermeasure, a risk for early containment failure still exists; this gives a classification of **high priority**. The running activities should be continued. A link exists to the issue ERI 4,1, the hydrogen combustion following a DCH.

ERI 3,5 issue concerns the formation of cracks and leakages at penetrations in concrete shells of containment. The goal is the estimation of leakages of fission products and possible retention, mainly in concrete wall cracks. Therefore the determination of the number of formed cracks and of their geometrical characteristics is important. The difficulty is to define a typical crack with crack width, length and shape. Further on the behaviour of leakages in failed composite and steel liners is of interest. The retention of aerosol in cracks and its impact on the source term is treated in WP 15; analytical structure mechanics is investigated under steam explosion in the cavity (WP13-1).

For the formation of cracks in the concrete containment wall a significant overpressure needs to be established, which is significantly higher than the design pressure. This could happen due to a hydrogen detonation, but this load gives a very short momentum of about 10 ms, which might not influence the concrete with its low eigenfrequency. So the only threat for crack formation in the wall is the quasistatic long-term overpressure. Exceeding the design pressure will be avoided by the AM measure ‘containment depressurisation’. So the probability of crack formation is rather low.

Nevertheless the decision at the last SARP meeting about the new priority - it was already of 2. order - was left open due to missing expertise. The partners were asked to clarify and to express their interest, if the issue shall remain and with what priority.

ERI 4,1 issue concerns the melt ejection from the failed vessel into the cavity and further into containment or neighbouring compartments (DCH) even under moderate pressure in the vessel. The phenomenon is combined with hydrogen production due to oxidation processes of the melt droplets with steam in the cavity, adjacent compartments and the containment atmosphere and its combustion together with pre-existing hydrogen. The investigations are aiming to increase the knowledge on parameters affecting the pressure build-up and to determine the risk of containment failure. Activities are treated in WP13-2 (DCH) and 10-2 for vessel failure (OLHF benchmark, boundary conditions for DCH, interpretation of FOREVER results, links to ISTC project). The results of DISCO and other experimental programs show a strong dependency on the simulated geometry. An experimental database exists and CFD codes can be used for analysis with reasonable results. The hydrogen combustion simulation needs to be improved. This is linked to ERI 3,4 (H2 combustion modelling).

Due to the threat to containment integrity the issue has high priority. The issue is partially closed; it is solved for the plant types EPR and VVER1000, but it is open for KONVOI plant type. The scaling effect is still open. Analytical effort is needed for the determination of the initial hole size, the ablation of the hole and the simulation of the H2 combustion in conjunction with DCH. The work is recommended to **be continued at reduced effort**.

ERI 5,1 issue concerns the impact of the oxidising environment on the source term, in particular Ru for high burn up fuel and MOX fuel elements. The different items are treated in the WP14-1 oxidizing environment on the source term by different experimental activities in the Ru circle (VTT tests, AEKI tests, AECL tests, INR FIPRED tests, CEA MERARG-Ru test). Links exist to the ISTC project e.g. through the VERONIKA proposal; in WP9-3 Zircaloy oxidation by air and by steam-air mixtures is investigated (QUENCH, MOZART). The CEA VERDON series, now in the planning stage, should also provide relevant data.

As Ru can influence the source term significantly the work has a **high priority**. The issue is covered by ISTP and the work should be continued as planned.

ERI 5,2 issue concerns the high temperature chemistry in the RCS and its impact on the source term. The prediction of the iodine species exiting the RCS shall be improved to provide the best estimate of iodine source into the containment.

ERI 5,4 issue concerns the chemistry of iodine in the containment and its impact on the source term.

Both issues were combined because they treat the iodine chemistry and the treatment and formation of volatile FPs like iodine and Ru. Both issues have to be looked at in a common way. In WP14-2 the high temperature chemistry of iodine is treated in the circles SIC (silver-indium-cadmium impact on iodine chemistry turned out to be 2. order) and I-RCS (iodine in RCS). In WP9-2 the source from the bundle in the early core degradation phase is investigated. WP16 treats the chemistry of iodine in the containment. The RUTH circle in WP16 treating the Ruthenium behaviour and the IPAR circle treating the possible production of molecular iodine from CsI, when passing through a recombiner at high temperatures are of strong interest. The issues are covered by these activities and also by ISTP and other projects. These activities are further on classified with **high priority**, because they are still relevant for the source term and risk significant. The work shall reduce the uncertainties in the iodine release part. In PWR containments the temperatures are expected not to be so high, but for the BWR containment high temperature chemistry is an item, because the heat up of a smaller containment volume and the risk of possible fires are expected to be higher.

ERI 5,3 issue concerns the aerosol behaviour and its impact on the source term. The effect of uncertain key aerosol phenomena on the source term shall be quantified. Emphasis is placed on aerosol retention in the secondary side of steam generator during SGTR sequences and in cracks of concrete containment walls, on the revaporisation and revolatilisation of previously deposited aerosols in the RCS and in the containment. These items are treated in WP15. In comparison to the volatile FPs the aerosol contribution to the source term is of second priority.

For the direct impact on source term the release through failed SGTs is important as release path passing by the containment. Due to the AM measure ‘Filling the SG secondary side’ the aerosols and FPs will be trapped in the water by the scrubbing effect. To quantify and ensure this effect validation of models is necessary and the running activities should be continued. It is important to quantify and to ensure a decontamination factor of orders of magnitudes by scrubbing, and not so relevant if the decontamination changes only by factors less than 10 by depletion and resuspension processes. Therefore the validation of scrubbing models and its improvements should be continued. For the retention in concrete cracks the explanation for the lower probability was given under ERI 3,5. Revaporisation and revolatilisation needs an estimation of the impact on the source term for plant conditions. This remobilisation itself is an effect, but compared to other contributions to the source term it might be of minor significance (note: relevance to a late source term).

The aspects of the issue are so manifold, that it should be carefully checked, if they are completely covered by the running activities. These activities should be followed, as it is done in ISTP, ARTIST and other projects, but **no further major efforts** in SARNET are needed.

ERI 5,5 issue concerns the characterisation and quantification of the FP release due to reflooding of the degraded core. This item is not experimentally treated in SARNET, but the issue is investigated in the ISTC VVER QUENCH project, which is to be continued. With respect to risk significance it is of second priority, because reflooding is not regarded in PSA 2 as a dominant effect.

F Conclusions

The reassessments of the priority ranking of the ERI issues were discussed during the last SARP meeting at FZK Karlsruhe on February 28th 2007.
Six issues are regarded to be investigated further with **high** priority:

- combined research on ERI 1,2/1,3a (core coolability during reflood and debris cooling, corium coolability in lower head
- combined research on ERI 2,1/2,2 (ex-vessel melt pool configuration during MCCI, ex-vessel corium coolability by top flooding);
- combined research on ERI 3,1/3,2 (melt relocation into water, ex-vessel FCI);
- research on ERI 3,4 (hydrogen mixing and combustion in containment);
- research on ERI 5,1 (oxidising impact (Ru oxidising conditions/air ingress for HBU and MOX fuel elements) on source term);
- combined research on ERI 5,2/5,4 (iodine chemistry in RCS and in containment).

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

- research on ERI 1,1 (hydrogen generation during reflood and melt relocation in vessel)
- research on ERI 1,4 (integrity of RPV due to external vessel)
- research on ERI 4,1 (direct containment heating)

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

- research on ERI 1,3b (corium coolability in external core catcher)
- research on ERI 1,6 (corium release following vessel rupture)
- research on ERI 5,3 (aerosol behaviour impact on source term (SGT and containment cracks)
- research on ERI 5,5 (core reflooding impact on source term)

Three issues are marked as ‘issue could be closed’. Due to the current risk significance and the state of knowledge no further experimental program is needed.

- research on ERI 1,5 (integrity of reactor coolant system and heat distribution)
- research on ERI 2,3/2,4 (ex-vessel core catcher and corium-ceramics interaction, cooling with water bottom injection)
- research on ERI 3,3 (FCI incl. steam explosion in weakened vessel)

The described reassessment has to be confirmed for genuine rendition at first by the group. They will be incorporated as the outcome of the reassessment process on the EURSAFE issues in the D67 deliverable, which can be regarded as an interim report on the research priorities. After confirmation by the group the draft of D67 will be circulated to the Management Team and the end users for comments and iteration, before the final reassessment will be released. The work performed in the SARP group is an attempt to come in a reasonable time under consideration of all useful co-determination to an agreed decision considering all aspects of innovation and economic efficiency. The D67 report will serve as a proposal to provide the Governing Board of SARNET with arguments for defining the orientations for the further joint activities for research of common interest and high priority.

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