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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

IDENTIFICATION OF RELEVANT CONDITIONS AND EXPERIMENTS FOR FUEL-COOLANT INTERACTIONS IN NUCLEAR POWER PLANTS

SERENA Co-ordinated Programme (Steam Explosion Resolution for Nuclear Applications)

The complete version is available in PDF format only

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OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA
Phase 1

TASK 1 FINAL REPORT

Identification of Relevant Conditions and Experiments for FCI in NPP's

SUMMARY

This report documents the findings of Task 1 of the international OECD programme SERENA. It is the first deliverable of the programme. It contains the individual contributions of the partners to the task and a synthesis of the results by the Programme Coordinator. General information on the programme and work content of Task 1 are given at the beginning of the report.

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GENERAL INFORMATION ON SERENA

SERENA (**S**team **E**xplosion **RE**solution for **N**uclear **A**pplications) is an international OECD programme for the resolution of FCI remaining issues.

Background

The programme has origin the concerns expressed by the Senior Group Experts on Nuclear Safety Research and Programme (SESAR/FAP) about de-emphasis of FCI research all over the world, while uncertainties still exist on some aspects of FCI. After an evaluation of remaining needs by FCI experts in a meeting October 2000, a proposal was matured during 2001 following CSNI recommendations that existing knowledge should be carefully assessed before carrying out new experiments, and reactor application should be the focus of any new action.

The work programme was approved by CSNI December 2001.

The programme started January 2002.

Objectives

The overall objective of SERENA is to obtain convergence on the understanding of FCI processes and energetics, as well as on method(s) for reliable estimate of the magnitude of loadings for realistic reactor conditions, in order to bring understanding and predictability of FCI energetics to desirable levels for risk management.

Strategy

The work is performed in two phases:

- **Phase 1** analyses and evaluates knowledge and data on FCI by using available tools with the aim to identify areas where large uncertainties/ discrepancies still subsist and are important for predicting loads in reactors with a sufficient level of confidence, and work to be done, if any, to reduce these uncertainties/discrepancies.

- **Phase 2** will implement analytical and experimental actions to resolve these uncertainties/discrepancies, if required.

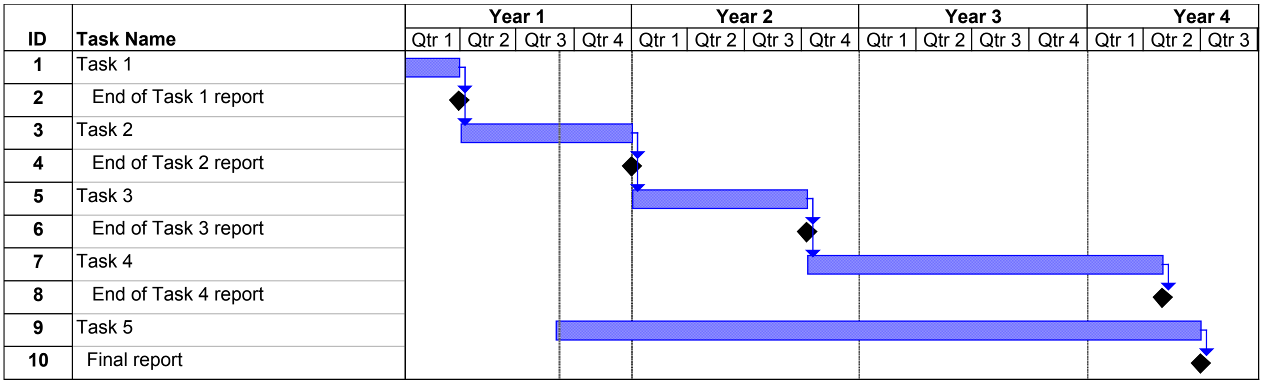
Work Programme of Phase I

The objective of Phase 1 is reached through comparative calculations by available tools of existing experiments and reactor cases. It is divided into **five tasks**:

1. Identification of relevant conditions for FCI in reactor
2. Comparison of various approaches for calculating jet break-up and pre-mixing,
3. Comparison of various approaches for calculating the explosion phase,
4. Reactor applications,
5. Synthesis and recommendations.

Organisation and planning of Phase I

Phase I is a **coordinated action**. It started January 2002 and has duration 3.5 year. The time table and deliverables are given below.



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A Programme Coordinator is in charge of coordinating and monitoring the work. A Technical Programme Committee assists the Programme Coordinator and provides wide technical and international support.

Each partner organisation of Phase I finances its own work. The total (3.5 years) manpower of Phase 1 is estimated at 1.2 person-year for each organisation carrying out the work. The total (3.5 years) coordination effort is estimated at one person-year. The coordination costs are financed jointly by CEA and IRSN.

Partnership of Phase I

The following organisations are partners in SERENA Phase I.

- IRSN (Institut de Radioprotection et Sûreté Nucléaires) and CEA (Commissariat à l'Energie Atomique), France (joint participation).
- FZK (ForschungsZentrum Karlsruhe), Germany.
- IKE (Institut für Kernenergetik und Energiesysteme der Universität Stuttgart), Germany.
- JAERI (Japan Atomic Energy Research Institute), Japan.
- NUPEC (Nuclear Power Engineering Corporation), Japan[1].
- KAERI (Korea Atomic Energy Research Institute) and KMU (Korea Maritime University), Korea (joint participation).
- KINS (Korea Institute of Nuclear Energy), Korea.
- NRC (Nuclear Regulatory Commission), United States of America.
- VTT (VTT Technical Research Centre), Finland.
- EREC (Electrogorsk Research and Engineering Centre on NPP Safety), Russian Federation.

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[1] NUPEC joined the project after completion of Task 1.

WORK PROGRAMME OF TASK 1

Objective

Identify the range of conditions relevant for energetic FCI in reactors and select existing experiments which best address these conditions for both the pre-mixing and the explosion phases in view of their calculations by available FCI codes in Tasks 2 and 3.

Description of work.

- According to his/her experience and/or peculiarities of running plants in his/her own country, each partner identifies the range of conditions which may result in an energetic FCI with potential damage to the reactor structures. He/She classifies these conditions in order of importance for safety.
- Each partner identifies existing integral experiments addressing these conditions and selects the most appropriate, from his/her point of view, for code calculation and comparison for both the pre-mixing and the explosion phases. Selection criteria should include the following:
    - Relevance to reactor conditions
    - Quality of data
    - Level of characterisation of initial conditions
    - Used materials
    - Unresolved discrepancies with previous calculations

  Partners indicate precise test numbers in a series which best satisfies the conditions, justify their choices and establish a classification for both pre-mixing and explosion.
- Each partner sends his/her contribution to the project coordinator.
- The coordinator establishes a draft synthesis on the basis of the contributions of the partners and proposes a ranking of the experiments for both pre-mixing and explosion, The document includes the partners' contributions as an appendix. It is distributed to the partners and to the technical committee about 0.5 month before discussing it in a meeting[2].
- The document is presented and discussed at the meeting, and the tests to calculate are selected :
    - One pre-mixing test
    - One explosion test (tentative choice to be finalised at the end of Task 2)
    - One integral test having both pre-mixing and explosion components.

  Note that the number of experiments is believed to be sufficient for the required purpose and consistent with the time window of the project.

  It is verified that the selected test data are equally available to each partner.
- The coordinator finalises the draft synthesis, which includes the tests selected for calculation. The document is distributed to the partners and to the technical programme committee for endorsement, and approval by CSNI. The technical programme committee forwards the document to the Working Group on Analysis and Management of Accidents (GAMA), for information, further technical discussion, and possible recommendations.

Deliverables

Synthesis document indicating and justifying the choice of the experiments to be used for calculations in Tasks 2 and 3, with the individual contributions by partners as an appendix.

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[2] Summary record of the first meeting of the SERENA Expert Group, 15-17 April 2002, IRSN, Fontenay-aux Roses, France, NEA/SEN/SIN/AMA(2002)13 (June 2002)

OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in NPP's

Synthesis of the Partners' Contributions

(as finalised at Task1 meeting)

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SUMMARY

Ex-vessel, energetic FCI occurring during melt discharge through a large breach in the lower head into a flooded cavity is of most concern. In-vessel, multiple jets through the core support plate are potentially the most challenging for the primary circuit in case of energetic FCI. SERENA will therefore aim at verifying the capabilities of the codes to predict these situations with a sufficient level of confidence. The status of the predictive capabilities of the code and associated uncertainties will be verified and compared first on relevant experiments for the two main phases of a steam explosion, i.e., pre-mixing and explosion. FARO L-33 is selected for analysis as the integral experiment including both the pre-mixing and explosion phases. FARO L-28 is selected for analysis as the pre-mixing experiment. Pre-mixing experiments PREMIX-16 and FARO L-31 are proposed for analysis on a voluntary basis. Typical explosion experiment(s) will be selected at the end of Task 2. In general the quality of available data is considered sufficient, but quantitative data are lacking on the internal structure of the pre-mixing phase.

1. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

1.1. Preliminary remarks

Even though SERENA is an unprecedented coordinated worldwide effort for converging towards a common understanding of FCI for reactor situations, resources of phase I are rather limited. The few calculations envisaged will not allow to cover all the spectrum of relevant situations.

With this in mind, it might be convenient to research those conditions that can bound most situations. Letting aside the diversity of reactor types and designs, the very fact that SERENA exists indicates that this research is far from being straightforward. At the best, one can extrapolate from present knowledge by using one or another method (evaluation with existing tools in their present state of validation, expert judgement…), and the confirmation that the anticipated choices were right can come only at the end of the process, and possibly require some iterations.

Most partners have, either implicitly or explicitly, used a similar approach in defining the relevant conditions for their reactor plants, sometime using also probabilistic assessment. However, probability aspects will not be directly addressed here.

1.2. Generic situation

In a broad sense, **steam explosion occurring sometime during the penetration of a large amount of core melt into a pool of water** is considered by all participants as a **bounding case** for FCI in reactor conditions, with one exception: steam explosion occurring during reflooding a molten debris in a weakened lower head (sometimes referred to as "stratified steam explosion"). However, the latter case is not considered as a major FCI issue by most of the partners, and the former more critical anyway.

Consequently, SERENA will address **melt-into-water** situations only, and the objective of the programme will be fully reached if reached for this type of melt/water contact.

1.3. Specific conditions

The next step is to identify which conditions might in turn bound this particular type of FCI, and here a distinction should be made between in-vessel and ex-vessel situations.

Table 1 summarises partners' interest for melt-into-water situations as a function of reactor type and either in- or ex-vessel FCI's, and Table 2 the conditions that are the most relevant as a function of the partners' specific reactor types and safety requirements.

1.3.1. Ex-vessel situations

From Table 1, it is seen that **ex-vessel situations** are of interest for all the partners, and from the single contributions it comes out that they **are of major concern** for most of them. The main reasons are one or more of the following:

- Failure of lower head in case of core melt down cannot be ruled out for most reactors;
- Absence of water in the cavity cannot be guaranteed at time of lower head failure;

- Flooding the cavity in case of expected vessel failure is already part of some SAM strategies;
- Use of water to cool down the debris in the cavity could be generalized if it is demonstrated that energetic FCI has no consequences on the containment integrity.

When integrating Table 2 data, the situations of concern for ex-vessel energetic FCI are unconstrained large pours of UO2-ZrO2-Zr-Steel melts in a deep pool of subcooled water at low system pressure and moderate driven pressure. Two classes of conditions can be established:

1. Single pour of some tens of centimeters in diameter
2. Multiple jets, each jet having a diameter of the order of 10 cm (in the case of penetrations in the lower head)

In the first category, a side pour is believed to be the most challenging for the cavity structure in case of steam explosion triggering "at the right time" (because of the vicinity of supporting structures). In the second category, jets falling at once as a compact array but just non-interfering each other is believed to be the worst case. It is beyond the scope of this synthesis to detail all processes and compensating effects that can affect the FCI behaviour of the two configurations, but the state of the art does not allow today to conclude which category can potentially lead to most energetic events.

Consequently, the following generic situation will be considered as **the reference case for ex-vessel FCI** :

> **Large pour equivalent to some tens of cm in diameter of UO2-ZrO2-Zr-Steel melts into a cavity flooded with subcooled water.**

Note that melt quenching induced steaming (without steam explosion) is also an issue for some reactor designs having containments of reduced volume. This situation can be considered as a sub-group of pre-mixing.

1.3.2. In-vessel situations

In-vessel FCI is of concern with respect to:

- Alpha-mode failure
- Lower head failure mode
- Consequences it may have on primary circuit (essentially damage on piping and steam generator) and debris distribution.

When integrating Table 2 data, the situations of concern for in-vessel energetic FCI are gravity pours of UO_2-ZrO_2 melts in the lower head in a ~2-m-deep pool of saturated water at moderate system pressure.

Here again both single and multi-pours are of concern. However **multi-jet configuration arrives first here**. Typically, it corresponds to a situation where a large breach forms in the crust of the in-core molten debris, giving sufficient melt flow to feed simultaneously several tens of core support plate holes (diameter of the holes of the order of 0.10 m). It is generally considered that the water in the lower head arrives up to the lower plate at the most.

In contrast with ex-vessel situations, in-vessel single pours are believed to be possible only through holes having a diameter of the same order than for multi-jet case. Consequently, multi-jet configurations are considered potentially more energetic than single pours. It is not clear however from the contributions whether this is the result of evaluations made by using available FCI tools (however in principle not qualified to address these conditions) or on single summing up considerations.

The reality is certainly not so straightforward, and depending on the distribution of the jets some counter effects, such as the production of highly voided regions inside the array of jets (if not completely voided), the potential for a very strong explosion may decrease dramatically.

In both cases, either single or multi-jets, jets arriving off-centre in the lower head are considered the most challenging for the vessel. On the contrary, side pours such as through the downcomer, are not considered as an issue with respect to steam explosion because of the limited amounts of melt which can be mixed with water at once.

Summing up, **the reference case for in-vessel FCI** will be:

Multi-jets of about 10 cm in diameter of UO2-ZrO2-Zr melts into the lower head.

1.4. Consequences

The reactor calculations of Task 4 will be performed for these two reference cases. The specific conditions of the calculations will be finalised during the course of the project.

The objective of SERENA phase 1 will be reached if reached for these cases.

2. RELEVANT EXPERIMENTS

2.1. Preliminary remarks

In this section **the best we could extract today from existing data to cover the objective of the programme** is established. The very selection of the tests which can reasonably be analysed within the frame of SERENA is established in Section 3.

Table 3 summarises the experiment selection by the partners. For each, they are listed by order of priority, however without taking into account whether or not they belong to the in- or ex-vessel category. Experiments out of this table are not discussed.

The available data are in general considered of good quality, but quantitative data on pre-mixing geometry and component fractions are scarce in all the tests, with the exception of PREMIX for void fraction. In KROTOS, the poor quality of the jet before entering the water is the main drawback. In TROI, large uncertainties exist on the melt temperature.

No relevant multi-pour experiment exists. It is clear however that the state of validation of the FCI tools would make meaningless to apply them directly to such a situation, before assessing the single jet configuration.

It is clear also that not a single experiment encompasses all the situations of interest for single jet.

2.2. Integral experiment

FARO L-33 is today the only integral (pre-mixing + explosion) "large scale" explosion experiment relevant to reactor conditions for most of the parameters (in particular moderate lateral constraint, see details of FARO L-33 in Table 5).

2.3. Pre-mixing experiments

Based of the discussion in Section 1, analysing three experiments, namely, **FARO L-31, PREMIX-16 and FARO L-28,** would match the criteria of the best we can extract today from existing data to cover the objective of the programme.

If we consider that ex-vessel steam explosion is of major concern, experiments which approach the fundamental requirements for ex-vessel situations (namely, **pours of UO2-ZrO2-Zr-Steel melts in a deep pool of subcooled water at low system pressure and moderate driven pressure)** should be selected as a first priority, with respect to those performed, e.g., with nearly saturated water and/or elevated pressure. This would also be consistent with the fact that most codes have major difficulties to calculate subcooled than saturated conditions, and with the fact that subcooled conditions have a major propensity to produce steam explosions.

It is also important, keeping in mind the purpose of SERENA, that the amount of melt involved, jet diameter, water pool depth and diameter be in the right proportion to each other with respect to reactor conditions in order to get access to most of the processes which might occur at the real scale.

From Table 3, **FARO L-31** is the experiment which approaches these criteria the best (see details Table 4), keeping in mind however that the melt is pure oxide and the water subcooling is a little high with respect to real conditions.

Important aspects of FCI in relation to reactor application are not covered by FARO L-31. They are:

- Role of material properties (including non-oxidised metallic phases)
- FCI in saturated water (mainly in-vessel cases but possible also ex-vessel for some designs)

Two complementary experiments would allow to cover both aspects: **PREMIX-16** and **FARO L-28** (see details Table 4).

By using significant amounts of alumina melt in conditions similar to FARO experiments, and recognising that corium experiments <u>of interest here</u> have all been made with 80 wt% UO_2 20 wt% ZrO_2 , the PREMIX series is presently the only possibility to test, <u>to some extend</u>, the role of melt physical properties on pre-mixing. In addition, PREMIX provides quantitative data on the extension of and void distribution in the mixing zone. PREMIX-16 seems the best suited.

FARO L-28 is complementary to PREMIX-16, with essentially the same test conditions and the same volume of melt but using corium instead of alumina. FARO L-28 is also complementary to

FARO L-31, being performed in nearly saturated water against subcooled water for FARO L-31.

2.4. Explosion experiments

As the final selection is expected to be made at the end of Task 2, explosions experiments will be discussed only briefly here.

The interest of this part of the programme is to focus on the description of the explosion phase. Thus, in addition to analysing the explosion phase of the integral test, it is important to verify and compare approaches and code/model performances on a coherent and strong steam explosion occurring in a relatively constrained (~1D) geometry. **KROTOS K-44 seems the most appropriate of the KROTOS series for such an exercise** (see Table 5).

As being presently the only running programme on FCI using corium, **TROI** offers a unique opportunity to perform a test as required by SERENA phase 1. The conditions of such a test could be decided at an adequate time during the execution of Task 2 and as a function of the relationships which can be established between TROI and SERENA. **TROI-13,** already performed, gives first-of-a-kind information concerning on the capability of prototypical corium to generate spontaneous steam explosion (see details in Table 5).

3. EXPERIMENT SELECTION FOR SERENA

According to the detailed work plan for phase 1 of SERENA and taking into account the limited resources given to the programme, partners agreed that **only the best suited test for each phase plus an integral test should be analysed[3].**

The integral test will be **FARO L-33** and will be analysed both separately for pre-mixing and explosion, and globally. This will tentatively result in:

- One global calculation of the integral test
- One calculation on the pre-mixing test
- One calculation of the integral test with imposed pre-mixing conditions
- One or two calculations of the explosion test depending on the conditions chosen to start the calculations.

For each calculation, detailed comparison between the calculation results and the data, and between the calculations themselves will be have to be performed by all partners and carefully documented.

With this in mind, and taking into account that FARO L-33 was performed with sub-cooled water in conditions similar to FARO L-31, **FARO L-28** performed with saturated water is proposed as the **reference test for pre-mixing** calculations. Thus, analysing pre-mixing for FARO L-33 and L-28 will allow to cover both saturated and sub-cooled water cases.

The other two tests of interest discussed in Section 2, **PREMIX-16** and **FARO L-31,** will be analysed on a voluntary basis.

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[3] D. Magallon, SERENA: Detailed work plan for Phase 1 of the programme. Annexed to the final proposal of the programme, 16/11/01.

A decision concerning the explosion test(s) to analyse is postpone to the end of Task 2, when the results of the pre-mixing phase analysis will be available and the possibilities of performing a TROI test for phase 1 of SERENA will be more precise.

Table 1. Partners' interests for melt-into-water situations

	PWR's/VVER's		BWR's	
	In-vessel	Ex-vessel	In-vessel	Ex-vessel
CEA-IRSN	X	X		
EREC		X		
FZK	X	X[1]	X	X[1]
IKE	X	X	X	X
JAERI		X		X
KAERI/KMU		X		
KINS		X		
NRC	X	X	X	X
VTT				X

[1] to a lesser extend

Table 2. Summary of melt-into-water most relevant conditions

	CEA-IRSN		EREC	FZK	IKE	JAERI	KAERI-KMU	KINS	NRC		VTT
Reference case	*In-vessel*	Ex-vessel	Ex-vessel	*In-vessel*	Most critical	Ex-vessel	Ex-vessel	Ex-vessel	*In-vessel*	Ex-vessel	Ex-vessel
Lower head geometry	*Hemispherical*	Hemispherical									
Pit geometry		Cylindrical								rather open	
Vessel diameter, m	*4.0 (inner)*	4.4 (outer)					4.2-4.7	4.2-4.7			
Pit diameter, m		5	5.5			6.0-6.3					
Jet configuration	*100 jets outer holes of core plate*	Single jet Central	Single jet Central	*Multi-jet*	Multi-jet, if not interacting	Single jet Central	Multi-jet	Multi-jet	*Single jet side pour*	Single jet Side or bottom	Multi-jet
Jet diameter, m	*0.07*	0.20-0.80	0.60-1.50	*0.05-0.08*	0.05-0.15	0.05-1.00	0.072	0.072	*0.1-0.5*		0.071
Jet entrance velocity, m/s	*< 20*	< 20			<10						15-22
Melt composition	*UO_2-ZrO_2 or UO_2-ZrO_2-Zr*				UO_2-ZrO_2-Zr-Steel	UO_2-ZrO_2-Zr-Steel	UO_2-ZrO_2-metal	UO_2-ZrO_2-metal	*Oxide*	Oxide-metal	UO_2-ZrO_2-Zr-Steel
Melt mass, 10^3 kg	*10-50*	20-40	50-170		100	109-270	66-110	66-110		1-several	
Melt temperature, K	*2320-2850*		2000-3000		2900-3000	2700-2800	2800	2800			
Melt superheat, K	*100-400*				50-150	<50	100-200	100-200	*100-200*	High and Low	
Melt flow rate, kg/s	*variable, duration 5-15s*				1000				*100's*		233-5000
Injection pressure, MPa	*Melt head*			*Melt head*			High and Low	High and Low		High and Low	
System pressure, MPa	*0.2-2.0*	0.1-0.3	0.1-0.5	*0.2-0.5*	<1.0	0.20-0.52	0.2-0.5	0.2-0.5			0.1
Atmosphere (initially)		Air				Steam, Air, N_2, H_2					
Water temperature, K	*near T_{sat}*		293-353	*T_{sat}*	Saturated and subcooled	350-390	320	320	*T_{sat}*		319
Water subcooling, K	*0-20*	20-50	80	*0*	Medium	71 (BWR) 3-43 (PWR)			*0*	depends on design	54 initially (sat. after 28s)
Water pool height, m	*0.7-2.8*	> 3	1.0-3.0		1.0-2.0 In-vess. < 10 Ex-vessel	5.0-8.2	1.5-6.85	1.5-6.85			8.3
Water mass, 10^3 kg	*10 to 23*										
Jet free fall in gas, m	*0-1.1*	< 1	2.5-4.5	*0*		0-4.5	0-5.35	0-5.35			

Table 3. Relevant experiments selected by partners (by order of priority)

Experiment type	Pre-mixing	Explosion	Integral
CEA-IRSN	FARO L-28 FARO L-31	FARO L-33 KROTOS 44 TROI (later)	FARO L-33
EREC	FARO L-33	FARO L-33 KROTOS 58 KROTOS 57	FARO L-33
FZK	PREMIX-16	KROTOS-44	FARO L-33
IKE	FARO L-33 PREMIX-16 FARO L-31	FARO L-33 KROTOS-44	FARO L-33
JAERI	FARO L-28 FARO L-31	FARO L-33 KROTOS-58 TROI-13	
KAERI-KMU	QUEOS-32 FARO L-14 FARO L-31	KROTOS-37 KROTOS-44 TROI-13	
KINS	QUEOS-32 FARO L-14 FARO L-31	KROTOS-37 KROTOS-44 TROI-13	
NRC	FARO L-19 FARO L-31 FARO L-11	KROTOS-38 KROTOS-45 KROTOS-58 TROI-13	
VTT	FARO L-24 FARO L-31 CCM -1, -3, -5 MIRA-20	No opinion	

Table 4: Conditions of pre-selected pre-mixing tests

Experiment	**FARO L-31**	**PREMIX -16**	**FARO L-28**
Melt and composition	80 wt% UO_2 20 wt% ZrO_2	90 wt% Al_2O_3 10 wt% Fe	80 wt% UO_2 20 wt% ZrO_2
Melt mass released	92 kg	60 kg	175 kg
Melt temperature	3000 K	2600 K	3053 K
Melt superheat	150 K	286 K	203 K
System pressure	0.22 Mpa	0.50 MPa	0.51 MPa
Water temperature	291 K	419 K	424 K
Water subcooling	106 K	5 K	0 K
Release diameter	0.05 m	0.048 m	0.05 m
Δp melt delivery	Gravity	Gravity simulation	Gravity
Free fall in gas space	0.77 m	0.22 m	0.89 m
Water depth	1.45 m	1.33 m	1.44 m
Test section diameter	0.71 m	0.69 m	0.71
Free-board	Closed volume (3.5 m^3)	Open volume	Closed volume (3.5 m^3)
Available data	• Melt jet characterisation in gas phase (visualisation) • Pressures and temperatures in gas and water • Melt leading edge progression • Water level history • Quenching rate • Global void fraction • H_2 production • Temperatures at bottom plate, • Debris analysis.	• Pressures and temperatures in gas and water • Melt leading edge progression • Water level • Steam production • Quenching rate • Geometry of mixing zone (form visualisation) • Local void at selected times • Debris analysis	• Melt jet characterisation in gas phase (visualisation) • Pressures and temperatures in gas and water • Melt leading edge progression • Water level history • Quenching rate • Global void fraction • H_2 production • Extent of mixing zone (form visualisation) • Temperatures at bottom plate • Debris analysis.

Table 5: Conditions of pre-selected explosion tests

Experiment	**FARO L-33**	**TROI-13**	**KROTOS-44**
Melt and composition	80 wt% UO_2 20 wt% ZrO_2	70 wt% UO_2 30 wt% ZrO_2	10 wt% Al_2O_3
Melt mass released	100 kg (40 kg at trigger)	7.7 kg	1.45 kg
Melt temperature	3070 K	~3300 K	2673 K
Melt superheat	220 K		359 K
System pressure	0.41 MPa	0.1 MPa	0.1 MPa
Water temperature	294 K	292 K	363 K
Water subcooling	124 K	81 K	10 K
Release diameter	0.05 m	0.02 m	0.03
Δp melt delivery	Gravity	Gravity	Gravity after crucible impact
Free fall in gas space	0.77 m	3.9 m	0.43 m
Water depth	1.62 m	0.69 m	1.115m
Test section diameter	0.71 m	0.60 m	0.20
Free-board	Closed volume (3.5 m^3)	Closed volume (8.03 m^3)	Closed volume (0.23 m^3)
Trigger	Yes (at bottom)	No	Yes (at bottom)
Available data	• Melt jet visualisation in gas phase • Pressures and temperatures in gas and water • Melt leading edge progression • Water level history • H_2 production • Propagation of energetic event after triggering, • Temperatures at bottom plate • Debris data.	• Melt jet visualisation in gas phase • Pressures and temperatures in gas and water • Debris data	• Pressures and temperatures in gas and water • Melt leading edge progression • Melt leading edge progression • Water level history • Propagation of energetic event after triggering, • Temperatures at bottom plate • Debris data.

OECD RESEARCH PROGRAMME ON
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SERENA

TASK 1

Identification of Relevant Conditions and Experiments For FCI in Npp's

IRSN / CEA Contribution

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Summary

In the frame of French reactors, IRSN and CEA have selected two different conditions where an energetic FCI might occur. We can briefly qualify them as the In-Vessel and Ex-Vessel conditions. These two conditions are described in terms of prototypic range of conditions under which an energetic event may happen.

Concerning the reactor calculations, some principles are proposed for the methodology to run the cases and representative cases are proposed.

These two aspects are expressed in the first chapter.

In the second and third chapter, the characteristics of relevant experiments are presented and specific experiments are proposed for the SERENA exercise.

Comparing reactor conditions with the experimentally covered domain made us feel necessary to add a chapter four, which would be a preliminary contribution to the synthesis in task 5.

1. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

1.1. Generic description of relevant reactor cases

Following the French experience in Reactor Safety, two generic situations have been isolated, so that they should cover the largest range of different plausible conditions. These two situations will be denoted as In-Vessel and Ex-Vessel situations.

Basically, the In-Vessel situation involves a multiple corium jet injection, with small diameters, in a low pressure, nearly saturated environment. The corium jets pour under gravity conditions. The Ex-Vessel situation considers an injection of a large stream of corium, i.e. some tens of centimeters for the diameter. In this case, the injection velocity is conditioned by the vessel pressure and might be higher than if controlled by gravity. However, we propose to restrict the calculation to a low pressure driving case. In this case, the water should be sub-cooled by at least 20 K.

1.2. Methodology for reactor calculations

For each case, the procedure might be the following:

- One complete premixing calculation, up to the complete deposition of the fuel on the bottom.
- Two explosion calculations:
    - One starting with the conditions given by the premixing calculation, at a given time;
    - One starting with the conditions given by one among all different premixing calculations (i.e. to be chosen among all different code calculations, each explosion calculation is starting with the same conditions).

The first explosion calculation should give the result for the complete sequence (premixing + explosion) for each calculation, whereas the second calculation would lead to the comparison of the explosion calculation only.

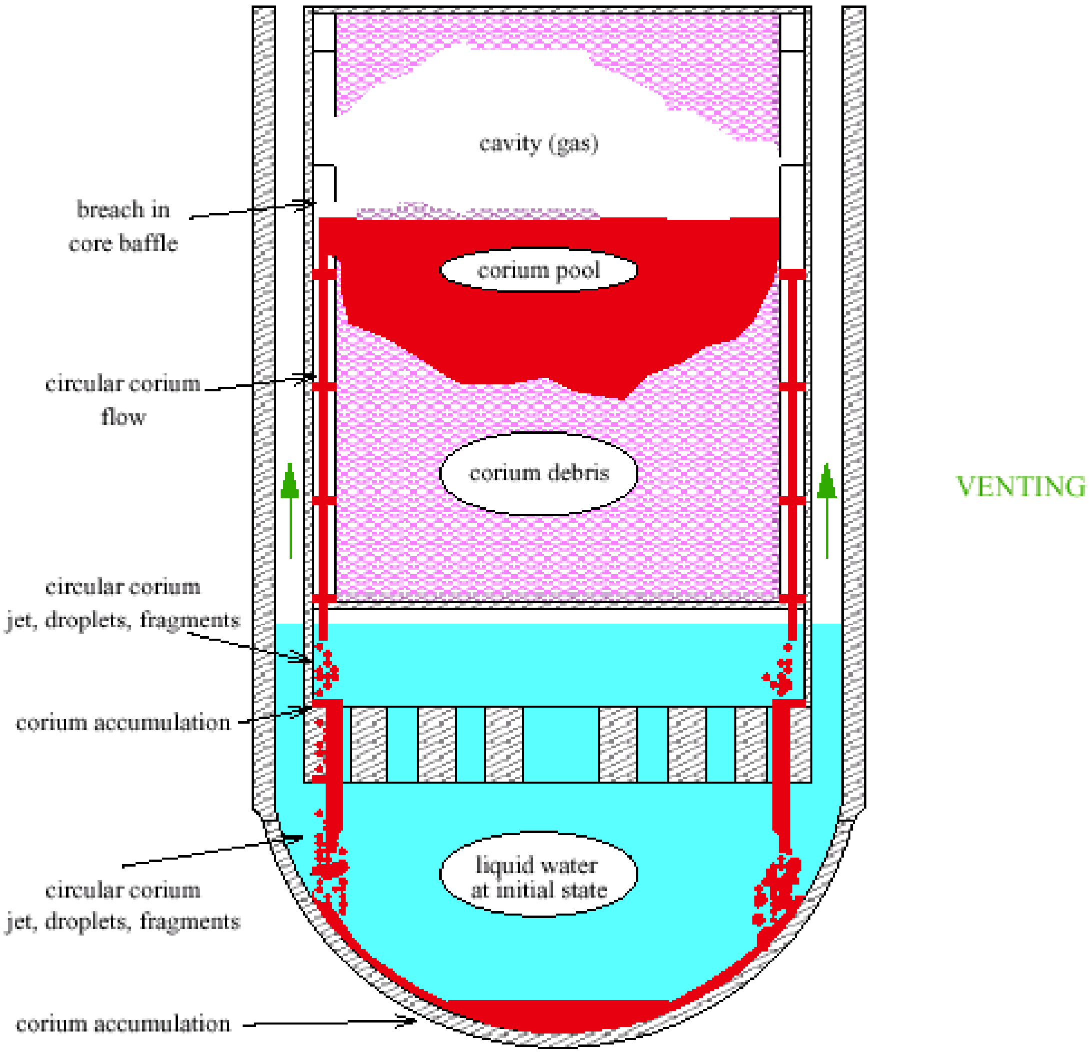
For the In-Vessel case, the time of explosion triggering is open to reflection. In the Ex-Vessel case, we propose to trigger the explosion at the time when the melt contacts the bottom.

1.3. In-Vessel situation.

The initial and boundary conditions for the in-vessel FCI come from the PSA level 2 in French 900 MWe PWR.

The situation is depicted in the following figure.

The corium flows through the outer holes of the lower core plate; so a circular set of jets falls into the lower plenum, which is full of water. The dowcomer is providing venting.



CORIUM RELOCALISATION FROM POOL INTO LOWER PLENUM

longitudinal section of the 900 MWe PWR vessel

The simplified geometry of the 900 MWe PWR lower plenum vessels where the FCI takes place can be described with:

The diameter of the hemispheric lower head: $\Phi_L = 4$ m

- The down comer inner diameter: $\Phi_{d,in} = 3.4$ m, and outer diameter $\Phi_{d,out} = 4$ m

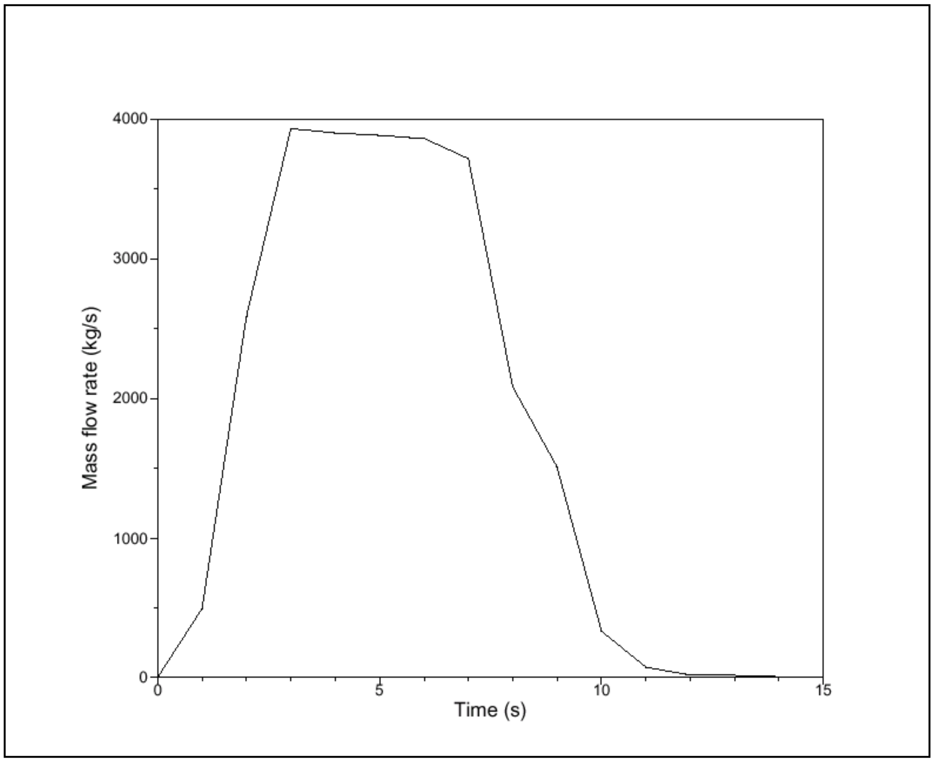
The lower core plate (location of the corium inlet in the lower plenum) diameter: Φ_p = 3,40 m, height from the bottom head vessel H_p= 2,80 m

The corium flow is characterized by:

- Its composition: oxide corium (e.g. 80%w UO_2, 20%w ZrO_2) or metallic corium (e.g. 65%w UO2, 21%w ZrO2, 14%w Zr) which defines its thermalhydraulic properties
- Its temperature beyond the liquidus temperature: $\Delta Sup \in$ [100, 400 K]
- Its mass flow rate $Q_c = f(t)$ (e.g. curve below) poured in a duration $d \in$ [5 s, 15 s]
- Its total mass $M_c \in$ [10 t, 50 t]
- Its flow shape: about one hundred jets ($\Phi_j \approx$ 7cm) flow through the lower core plate on the circle ($\Phi_f \approx$ 3,2 m)
- Its flow section total area S_c = 0,38 m^2

The water in the lower plenum is characterized by:

- The pressure in the vessel: $P \in$ [2, 20 bars]
- Its temperature and its sub cooling: $\Delta T_{sat} \in$ [-20 K, 0 K]
- Its mass: $Me \in$ [10 t, 23 t] and its height from the bottom head vessel $He \in$ [0,70 m, 2,80m]; so the free fall in gas $H_f \in$ [0 m, 1,10m]



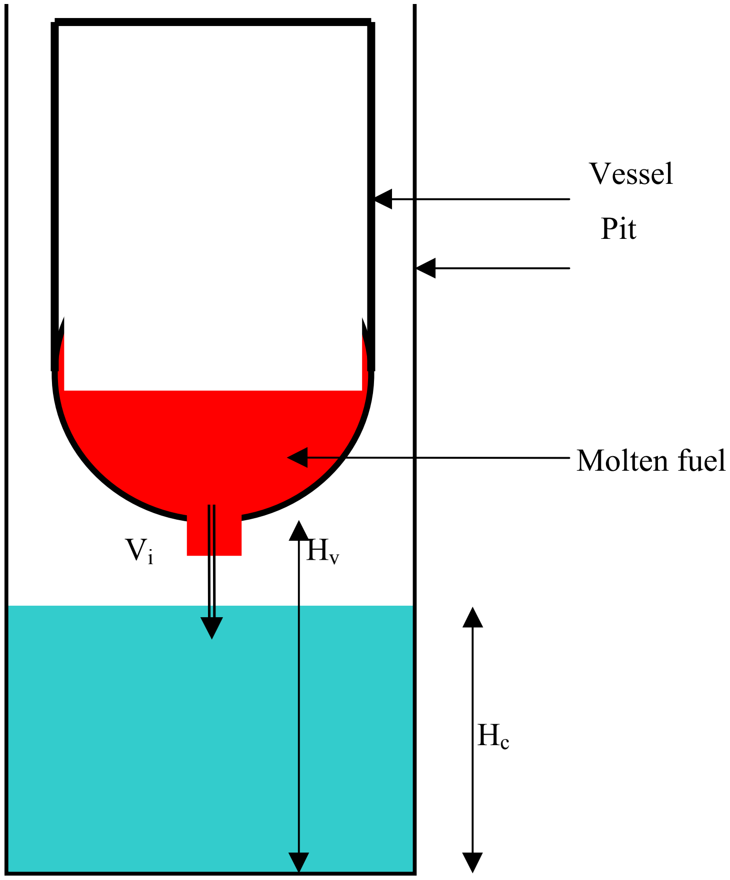
If we were proposing reactor calculations today, we would propose three reactor calculations:

	OCSW oxide corium saturated water	MCSW metallic corium saturated water	OCSW oxide corium sub cooled water
Corium composition	80%w UO2, 20%w ZrO2	65%w UO2, 21%w ZrO2, 14%w Zr	80%w UO2, 20%w ZrO2
Tliquidus	2850 K	2320 K	2850 K
Corium temperature	3250 K	2720 K	3250 K
Corium mass	26 t	26 t	26 t
Pressure	5 bar	5 bar	5 bar
Water subcooling	0 K	0 K	20 K
Water mass	23 t	23 t	23 t

First priority would be given to the MCSW case.

1.4. Ex-Vessel situation

This situation represents a simplified lower head failure event occurring with water in the reactor pit. A generic sketch of the situations is pictured in the following figure.
The injection might be represented by a boundary condition with imposed velocity and diameter.



The following table summarizes the different parameters for the premixing calculation.

Geometry		Typical simplified reactor geometry
	Vessel lower head geometry	Hemispherical
	Pit geometry	Cylinder
	Vessel radius	2.2 m
	Pit radius	2.5 m
	Vessel height	Hv = 4 m
Injection		Large stream with imposed velocity
	Jet diameter	20 to 80 cm
	Jet velocity	$V_j \leq 20$ m/s
	Total fuel mass	20 to 40 tons
Environment		Air + sub cooled water
	Coolant height	$H_v \geq 3$ m. (Free fall in gas < 1 m, coolant height up to flooded conditions)
	Coolant sub-cooling	$20 \text{ K} \leq \Delta T_{sub} \leq 50 \text{ K}$
	Pit pressure	1 to 3 bars
	Gaseous atmosphere	Vapour / Air

The fuel might be a prototypic corium, with a parametric associated oxidation possibility (to be defined).
The explosion might be triggered at the time of contact of the melt with the pit bottom.

If reactor calculation conditions were to be chosen at once, we would propose:

- Jet diameter = 50 cm
- Jet velocity = 10 m/s
- Pit initial pressure = 2 bar abs

2. RELEVANT PREMIXING EXPERIMENTS

As the conditions of interest for reactor accident seem to be “ large pours of corium - under a jet form - into water at “low sub cooling” (saturated for in vessel conditions and sub cooled for ex-vessel conditions), the choice of relevant experiments is very limited and indeed two of the available experiments fulfil these requirements:

- Large pour involving established jet of corium
- Low pressure.

They are the FARO TESTS L28 and L31 which are well documented and well characterized (well known boundary conditions i.e. mainly entrance conditions for the melt (initial velocity)) and which correspond to the physics described in our codes. However, there is a restriction which can be of importance for low pressure and sub cooled conditions (and even for saturated conditions but with a lower importance), it is the hydrogen production law which cannot be modelled precisely as the actual cause of this production is not really known. More, in the recent Korean TROI experiments with quite similar corium (70% UO_2, 30% Z_rO_2), no hydrogen production was observed. So, we think that we would have to admit that the measured hydrogen quantity is produced during the corium fragmentation sequence (jet to drops and smaller drops) and to introduce such a law in our codes.

For experiment-code comparison we have the following quantities:

- Pressure history in the gas dome (*****) (with the restriction due to H_2)
- Temperatures histories in the gas dome (****)
- Temperature histories in the "liquid" (****)
- Energy balances from the experimental team (***)
- Level swell (**)
- Penetration of the melt into water (****)
- Partition between cake and debris (****)
- Sauter mean diameter of the debris (****)

NB 1: the number of stars indicates the quality of the experimental data

NB 2: We also have to be aware that the thermal leaks – which are not taken into account in most, if not all, of the codes start to play a role early in the experiment so that 'long" term calculated values should be carefully compared to experimental ones.

3. RELEVANT EXPLOSION EXPERIMENTS

For explosion calculations, it would be desirable to choose an energetic test to "validate" as much as possible the explosion models and then to apply these models to a corium explosion test. To do so an alumina KROTOS test should be selected with the FARO L33 premixing- triggered explosion experiment.

For the KROTOS alumina test, the most energetic test seems to be test 44, which uses an external gas trigger and almost saturated water. An other test (38) was a little less energetic using sub cooled water and undergoes a spontaneous explosion. To calculate these KROTOS tests, we have to be aware that the experimental premixing sequence does not correspond to the physics described in our premixing codes so that calculations starting from premixing should not be relevant. It may be more interesting to initialise the explosion calculations using the global volume fractions given by the experimental team (for fuel from the measured penetration and time of trigger, for steam from level swell taking into account some uncertainties in this last measurement). To really compare the codes, it would then be desirable to both choose the same premixing state at the time of triggering and to analyse the sensitivity of the different models to variations of the premixing state.

The quantities to be compared are:

- Pressure traces at different locations (*****)
- Sauter mean diameter of the debris (****)
- Pressurisation in the expansion vessel (*****)

For the FARO L33 test, we should calculate the premixing sequence up to the time of triggering and then switch to explosion calculations. So we could compare premixing quantities (see previous paragraph) as well as explosion quantities such as pressure in the test section as well as in the FAT vessel. Propagation of the pressure peaks in the test section can also be analysed (Figure 5.8 of the Data Report). The shape of the debris accumulated at the bottom of the tank is also available as well as the Sauter mean diameter. Unfortunately, all the codes use rigid structure while in the experiment, some deformations occur allowing an attenuation of the pressure.

NB: The TROI experiments, when well documented, could also be of interest both for premixing and premixing plus explosion.

4. COMPARISON OF REACTOR EVALUATION NEEDS WITH EXPERIMENTAL DOMAIN

4.1. Premixing

The in-vessel premixing domain is correctly covered by the experimental domain in terms of jet diameter and jet velocity. However, the small distance between the jets induces an interaction between them. Concerning the premixing mass, the mass of each jet is larger in the reactor case with a factor of 2 when compared with the FARO tests. Moreover the total premixing mass is much larger in the reactor case. This multi-jet situation is asking for sensible evolutions in the jet model and in the jet experimental domain.

The ex-vessel premixing domain is also badly covered by the existing experimental data: the jet diameter and mass are much larger in the reactor case. However, the jet fragmentation processes might be the same as in FARO.

4.2. Explosion

For the in-vessel as well as for the ex-vessel situation, the masses that may be involved in an explosion are two orders of magnitude larger in the reactor case when compared with the experimental database.

However, this difference is felt to be less important than for premixing, which has to be considered with the first priority.

OECD RESEARCH PROGRAMME ON
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Identification of Relevant Conditions and Experiments for FCI in NPP's

EREC Contribution

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1. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

Investigations of FCI in Russia were mainly concentrated on analysis of ex-vessel FCI in the VVER-1000 cavity. VVER-1000 is a pressurised water reactor of Russian design. Typical range of geometric and physical parameters of ex-vessel scenario of FCI for VVER-1000 are following:

• Diameter of concrete cavity	~ 5.5 m
• Water level in the cavity	1÷3 m
• Free-fall distance of the melt jet	~ 2.5 – 4.5 m
• Diameter of the melt jet	0.6 – 1.5 m
• Corium mass	50÷170 t
• Temperature of the corium	2000 – 3000 K
• Water temperature	20 - 80°C.

Based on our experience and calculations with VAPEX code the most important conditions which may results in an energetic FCI are following.

I.1	Low pressure	1÷5 bar
I.2	High water level	3 m
I.3	High water subcooling	80 K
I.4	High corium temperature	3000 K

2. RELEVANT PREMIXING EXPERIMENTS

II.1 FARO test L-33

II.1.a Discharge of 101 kg of UO2/ZrO2 in subcooled water at 4 bar. No spontaneous steam explosion occurred, but a trigger was activated at 1.12 s which was able to generate a steam explosion in the mixture. The maximum pressure measured below the water level in the test section was 10.5 MPa. The values of the mechanical efficiency of the explosion are ranging between 0.39 and 0.5%.

References:

1. A.Annunziato, C.Addabbo, D.Magallon – 'FARO Test L-33 Quick Look Report' – JRC

Technical Note No. I.00.111, October 2000.

2. R.Silverii and D.Magallon – 'FARO LWR Programme. Test L-33 Data Report' – JRC

Technical Note No. I.00.124, October 2000.

II.1.b Test conditions are relevant to conditions of ex-vessel fuel-coolant interaction on NPP.

II.1.c Level of characterisation of initial and boundary conditions is high.

II.1.d Quality of data is good.

II.1.e The model of the hydrogen generation during FCI is required for correct prediction of pressure behaviour.

3. RELEVANT EXPLOSION EXPERIMENTS

III.1 Explosion stage of FARO test L-33

III.1.a See II.1.a

III.1.b Test conditions are relevant to conditions of ex-vessel fuel-coolant interaction on NPP.

III.1.c Initial conditions (distributions of melt, void fraction, temperatures and etc.) must be calculated with any premixing code. Characteristics of external trigger are known.

III.1.d Quality of data is good.

III.1.e Calculation results essentially depend on amount of hydrogen generated during FCI. Adequate model of hydrogen generation during premixing stage is needed for correct prediction of steam explosion.

III.2 KROTOS K-58

III.2.a Melt - UO2/ZrO2, mass - 4.5 kg, temperature - 3077 K, initial pressure - 3.7 bar, subcooling - 125 C. Maximum pressure – 25.8 MPa, energy conversion efficiency – 0.15 %.

> Reference: I. Huhtiniemi and D. Magallon "Insight To Steam Explosions With Corium Melts In KROTOS" NURETH-9 Conference Proceedings, 1999 October 3 rd – 8 th, San Francisco, California.

III.2.b Test conditions are relevant to conditions of ex-vessel fuel-coolant interaction on NPP.

III.2.c Initial conditions (distributions of melt, void fraction, temperatures and etc.) must be calculated with any premixing code. Characteristics of external trigger are known.

III.2.d Quality of data is satisfactory, window was damaged during the test, that probably gives some uncertainties.

III.2.e No calculations of this test were made.

III.3 KROTOS K-57

III.3.a Melt Al2O3, Mass 1.4kg - Temp. 2670 K Pressure 1 bar, subc. 83 C

> Reference: I. Huhtiniemi and D. Magallon "Insight To Steam Explosions With Corium Melts In KROTOS" NURETH-9 Conference Proceedings, 1999 October 3 rd – 8 th, San Francisco, California.

III.3.b Test conditions are not relevant to conditions of ex-vessel fuel-coolant interaction on NPP. Analysis of this test is needed for comparison with test K-58.

III.3.c Initial conditions (distributions of melt, void fraction, temperatures and etc.) must be calculated with any premixing code.

III.3.d Quality of data is satisfactory.

III.3.e No calculations of this test were made.

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TASK 1

Identification of Relevant Conditions and Experiments for FCI in NPP's

FZK Contribution

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Forschungszentrum Karlsruhe 23 February 2002

OECD Research Programme on Fuel-Coolant Interaction (SERENA)

Accident conditions in which an energetic FCI could occur

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1. In-vessel FCI with melt into water

a) Considerations

The highest potential for an energetic FCI occurs if, towards the end of the core melt-down phase, large amounts of molten core materials (corium) relocate into a water filled lower RPV plenum. This situation has led to the concern about α-mode failure. Today and from the technical point of view, α-mode failure is no longer a primary concern - either on the basis of probability arguments (e.g. [1]) or on basis of (essentially) energy arguments, e.g. [2]. But both approaches include a lot of 'expert judgement.' So their validity could be questioned and further improvements are required. Also, the topic must remain a point of concern from the ethic and the political points of view. This is because

a) In view of the supranational catastrophe that could be the consequence of an early containment failure, we must assure ourselves to the utmost extent that this cannot happen. A low probability is not sufficient!
b) A convincing proof of the impossibility of an α-mode failure that is mechanistic and verifiable is a precondition of a public acceptance of nuclear energy that is based on reasoning (however uncertain it may be that such a thing exists).

Completely independent of the above arguments, the in-vessel FCI remains an important topic in severe accident analysis, because even an FCI that is not able to create a large and energetic missile by ripping the vessel head off the reactor pressure vessel (RPV) may still have other serious effects in and on the primary coolant system, such as

a) failure of the lower vessel head under the action of the explosion pressure
b) failure of the vessel bearings (and possibly the main coolant lines) due to the downward and/or upward forces exerted on the pressure vessel
c) gross movements of the pressure vessel
d) ejection of water into the cold legs (already during premixing), leading possibly to water hammer effects on the piping (failure, whipping,...)
e) ejection of (quenched) corium particles into the cold legs (already during premixing)
f) acceleration of water slugs within the pipes by the explosion pressure which could have the same consequences as listed above for the injected water but with a higher intensity and could lead to damage of the steam generators, thus creating a containment bypass.

At any rate, an in-vessel FCI will

a) redistribute the corium within the pressure vessel and the primary coolant system (even ejection of unquenched corium into the hot legs is possible)
b) probably damage most of the in-vessel structures
c) possibly strain the lower vessel head plastically so that it were already damaged when a corium pool would be formed in it.

b) Conditions

If one assumes that the high-pressure path is prevented with certainty, the pressure within the primary system is below 2MPa at the time of melt relocation. Most probably it is within the range of about 0.2...0.5 MPa. The water in the lower plenum is most probably saturated at that pressure.

A large uncertainty exists concerning the way in which the melt relocates from the core area into the lower plenum. This depends mainly on the way in which the melt pool in the core area fails and thus is not well understood and cannot be well described at present. But there are indications that the melt pool will fail preferably at its upper/outer edge. This is mainly due to the distribution of heat flux to the boundary from a melt pool with internal heat generation and convection. (Mind: The melt pool in TMI-2 probably did not fail due to this process. Rather, the melt was squeezed out of the pool when the upper crust failed under the weight of the overlying rubble bed. So, naturally, the melt went 'over the rim' of the pool. The situation in TMI-2, where the pressure vessel was completely filled with water is absolutely untypical of a scenario in which the core melts after the water has boiled away.) In addition, modern reactors tend to have a very flat radial power distribution. This favors radial growth of a melt pool. (Mind: While the internal heat source within the pool is homogenized by the convective flow, the heat generation within the crust still depends on the heat source in the fuel pins engulfed by the crust and in material that has mainly moved axially.) This may lead to such a fast radial growth of the melt pool that the side boundaries of the core are reached before the pool contacts the lower boundary of the core. This would further increase the probability of a pool failure at the upper rim.

With sideways pool failure, the flow path of the corium towards the lower plenum depends on the design of the core former. If it is a welded construction with much internal space, the melt will flow down within the core former (like in TMI-2). If the core is surrounded by a heavy reflector (EPR), the melt will penetrate through heavy reflector and core shroud into the down comer and will flow down the down comer - probably at the vessel wall.

An important point is that sideways melt relocation from the pool in the core will probably lead to very low flow rates so that there remains almost no potential for an FCI with relevant pressure generation or energy release.

On the other hand, with the limited knowledge about the late phase of core degradation, it cannot be completely excluded that the 'classical' way of corium relocation occurs, i.e. downward corium relocation through the lower grid plate after a failure of the pool crust at the bottom. In this case, the static head of the melt pool itself would cause a fast melt flow and the melt would probably spread to some extent radially on the lower grid plate and then flow downward through the holes in the grid plate as a multitude of melt jets. (As the lower grid plate is a robust structure and well cooled until the failure of the melt pool, a failure of the grid plate together with the melt pool that could lead to a single large melt jet is highly improbable if not impossible.)

Premixing within the lower plenum might be influenced by structures within that volume (e.g. flow plates in PWR, guide tubes in BWR). But with downward melt relocation this effect should not be dominant.

2. In-vessel FCI with water on melt

a) Considerations

There is a certain chance that coolant is injected into the RPV after a melt pool has been formed there: either through the hot legs onto a melt pool in the core area or via the cold legs onto a melt pool in the lower plenum.

With the less dense water impacting the corium pool, the prospects for large-scale premixing are not very high. But if a melt pool in the core area is still enclosed by water from below, the spilling of water onto it could produce a break of the containing crust and a massive forced mixing with the water. So, a strong explosion could be induced. This might have a smaller potential to break the vessel head than an FCI in the lower plenum but all other consequences would essentially remain as described above. In the second case, the lower vessel head may have been (further) weakened by the thermal effects of the melt pool and even a not very strong FCI might lead to the failure of the lower vessel head. This would remove the possibility of in-vessel retention and, in case the reactor cavity would contain water, could lead to a further FCI in the reactor cavity.

The consequences of a pressurization of the primary coolant system as described under 1. above, may occur here as well.

b) Conditions

The conditions of an FCI with water into corium may possibly differ from those of corium into water by a somewhat lower system pressure (if it occurs later) and by subcooling of the water.

Also, the melt pool might be covered with a solid crust that would hinder or even prevent effective mixing.

3. In the reactor cavity (melt into water)

Here a wide variety of conditions is possible depending on the type of reactor (PWR / BWR) and the mode of vessel failure [hole(s), rip on the side, unzipping of lower head]. While the conditions applying to different reactor types can be accounted for in specialized analyses, the mode of vessel failure will remain an uncertainty and will probably require to study different cases.

The concerns with these FCIs are mainly
- structural damage to the side walls carrying the weight of the reactor vessel
- upward forces on the vessel itself and its bearings
- damage to doors/manholes leading into the cavity (if any).

While a complete evaluation of possible consequences of a severe accident must consider this situation as well, it may not be of primary concern if leak tightness of the cavity under all conceivable loads is assured by design measures.

4. FCI with water into melt in a compartment within the containment

If a larger melt mass should collect within a dry compartment [e.g. the reactor cavity, a core cooling device below the reactor vessel (if any) or the spreading area in EPR), an FCI could follow if a massive water flow into this compartment occurred. The consequences could be a pressure load on the walls of the containment including floor and ceiling, a redistribution of the corium, and its quenching - at least for some time.

In this situation a 'stratified' FCI (with a water layer on top of a melt pool) might occur. While these are expected not to involve very efficient mixing so that the consequences would seem to be limited, they might involve e.g. important redistribution of corium and they must be evaluated in a complete analysis of severe accidents.

Here again, a large variety of conditions is possible, depending on the design of the containment and the course of the accident.

5. General considerations

In addition to the possible consequences mentioned in the sections above, each FCI will most probably lead to a transient pressurization of the containment. This will primarily depend on the pressure-time history of the FCI itself and on the geometry of the flow path from the location of the FCI into the containment.

Pressure transients within the containment need to be analyzed so that a tool for analyzing the pressure-time histories of FCIs is required.

6. Conclusions

The case with most and most important potential consequences is the in-vessel FCI with melt into water. It might be that among these the ones with sideways melt relocation are more probable (frequent) than those with downward melt relocation. However, they can also be expected to be relatively benign. Furthermore, sideways relocation requires 3D analysis which is difficult to perform and certainly is not suited for parameter studies as might be helpful during the SERENA study. Also, with downward melt relocation, the generic problem of melt/water mixing is well adressed. So, downward melt relocation is the case to be considered.

Typically, downward melt relocation will lead to an array of relatively thin (e.g. 5...8 cm diameter) melt jets. A single jet of that diameter has a penetration depth of typically up to about 1.0...1.6 m at the speeds that are to be expected. (As demonstrated by the PREMIX experiments, the Saito formula gives a reasonable estimate of the jet penetration length of extremely high-temperature melts [3]). Within an array of jets, cross flow will occur which introduces a new mechanism for jet break-up that tends to disrupt the jet into relatively large globules. This will shorten the length of the continuous jet and diminish the importance of jet break-up along the shaft.

However, there are no experiments with arrays of jets. Only one experiment with 3 jets has been performed (PM11 [4]). So, we'll have to consider experiments performed with a single melt jet.
In experiments it has often been found difficult to produce ideal jets. In many cases there were effects that caused irregular melt velocities or oblique melt flow. But such conditions may not be too unprototypical. Of course, such conditions further reduce the importance of mechanisms that are observed on an ideal and smooth jet.

The other conditions are as described in 1b): pressure 0.2...0.5 MPa and water close to saturation. It is also prototypical to have a pool depth larger than the penetration depth of the melt jet(s) (which is violated in PM11). The free height between melt nozzle and water surface is typically small (virtually zero).

References:

1. Basu, S. and Ginsberg, T., “A Reassessement of the Potential for an Alpha-Mode Containment Failure and a Review of the Current Understanding of Broader Fuel-Coolant Interaction Issues”, NRC Report NUREG-1524, August 1996
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3. Kaiser, A., Schütz, W., Will, H., ”PREMIX Experiments PM12-PM18 to Investigate the Mixing of a Hot Melt being Poured into Water”, FZK Scientific Report FZKA-6380 (2001)
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OECD Research Programme on Fuel-Coolant Interaction (SERENA)

Proposal of tests to be calculated

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It was decided to choose for the recalculations:

- 1 premixing experiment
- 1 explosion experiment
- 1 integral experiment with both phases to be recalculated.

It occurs to be reasonable to choose the last one first because here the choice is most limited and this choice affects the other ones.

1. Integral experiment

For the purpose of the calculation exercise, we need an experiment in which the conditions of premixing are relatively well defined and in which a non-negligible explosive event took place. The number of such experiments is quite limited. The experiments performed in **FITS** (SNL), **ALPHA** (JAERI) and (so far) in **TROI** (KAERI) all suffer from a quite undefined geometry of the melt when entering the water. (In FITS and ALPHA, in addition, the composition of the melt is uncertain.)

In **KROTOS**, the situation is somewhat better. But in the early experiments in which the melt funnel was initially closed by a tin plate so that essentially gravity release occurred after its melting, the only information about the mixing process comes from thermocouples along the way of the jet and from level swell measurements. In the later experiments in which at least some visual observations are available, a sizable but unknown fraction of the mass is spilled at partly extremely high velocities. Also it has been detected that the mixing is quite different for the model corium and alumina, respectively. This difference is not yet understood and it might be that it is connected with the special release conditions. Therefore, KROTOS experiments are not a good test case for premixing calculations.

The **SUW** series of the MFTF tests (AEA Winfrith) might also be considered. Especially test SUW 09 apparently involved the coherent explosion of 75 % of the 24 kg of urania (containing 19 % of molybdenum) that were released. The mechanical energy amounted to almost 0.9 MJ. However, little is known about the mixing conditions and there is no information about the pressure-time history of the explosion itself, only about the cover gas pressure.

Another candidate might be the **WFCI** experiments (UWM) which included a device to measure the mechanical energy release. However, the melt masses used in these tests were relatively small, there is no detailed information about the mixing process, and mechanical energy results were obtained only for tests performed with tin, a very unprototypical material. The tests with the more prototypical iron oxide did not give explosions with energy release although some interaction pressures were registered.

At present, the obvious choice of an integral experiment is **FARO L-33**. This test has the advantage of involving a relatively large mass (41.6 kg) of a corium (80 % UO_2 + 20 % ZrO_2) that may be prototypical (is the most prototypical material used in tests until now). Also, the well defined trigger was followed by a clearly propagating interaction with pressures up to almost 100 bar at the vessel wall (radius 355 mm). An important disadvantage is that very little experimental information is available about the premixing process. But this disadvantage is mitigated by the use of the melt release facility of FARO which has been improved over many years and has reached a state in which well defined gravity release can be expected. Another disadvantage might be the relatively small initial melt superheat ($T_{initial}$ - $T_{solidification}$) combined with the late triggering time, 1.13 sec. This might mean that some of the fragmented corium had already frozen at the time of triggering and did not participate (wasn't finely fragmented) in the explosion, which might be part of the explanation of the relatively weak explosion. But this can be accounted for in calculations.

FARO test L-33 is at present the best choice for an integral experiment.

In the future, a further test performed within the ECO facility at FZK might also give a good study object. The last of these tests (ECO-04) involved about 10 kg of the alumina used as corium simulant in these tests (thus about 2/3 of the thermal energy in L-33) and produced an explosion with pressures up to about 400 bar and a mechanical energy of at least 180 kJ (this is definitely measured work done on the surrounding). The energy conversion was at least 0.5 % although no coherent interaction did occur. Rather there were three separate explosions at the bottom, the top, and again at the bottom of the test vessel. So, the whole event was spread over about 15 msec, allowing for a lot of parasitic steam condensation on the surrounding cold water (about 270 kg). The exact definition of the melt release time by the action of opening and closing valves together with pressure measurements in test vessel and melt generator allow to derive the melt flow velocity (about as well as from gravity action in FARO). The advantage of ECO as compared to FARO is the extensive instrumentation collecting information on the premixing process:

- thermocouples along the axial height close to the vessel center which indicate downward melt propagation (similar to KTOTOS)
- numerous void detectors in the gas space and the water pool indicating the presence of water or gas, respectively, thus also indicating the size and shape of the multiphase zone as well as, locally, the water volume fraction within it. The reliability of these indications can partly be verified with the help of the PREMIX tests in which the mixing process (multiphase zone) was observed visually.

2. Premixing experiment

Here the primary requirements are prototypical boundary conditions and complete characterization of the premixing process. The most important boundary conditions are melt temperature, system pressure and water subcooling. The exact nature of hot melt should not be overly important as long as it doesn't show behavior that clearly differs from that expected for corium. It is, therefore, indicated to use an oxide. The exact properties of that oxide like density, solidification temperature (temperature at which further coarse fragmentation is prevented), surface tension and viscosity can effectively be accounted for in most calculational models so that deviations of these properties from UO_2 should be no reason, not to use this material for tests.

Therefore I suggest to choose a **PREMIX** experiment as test case for this exercise. It has already been described above which techniques are used in ECO and PREMIX to monitor premixing. The void data are not available from any other experiment. Unfortunately, in PREMIX, we don't have slide valves to control the melt release. So, melt release is somewhat more uncertain in these experiments than in ECO. But this should be more than compensated by the extensive optical observation of the mixing process.

The most suitable test is probably **PM16** in which the water was saturated initially and 50 kg of melt have been released within 4.8 sec. (This test parallels FARO test L-28.) During the melt release, the pressure rose from the initial 5 bar to 7.7 bar (L-28: 5...16.6 bar). The test might be somewhat more difficult to analyze than FARO L-28 because there is no pressure equilibrium between the test vessel containing the water and the outer pressure vessel [which is much larger (220 m^3) than the FARO FAT vessel (3.53 m^3)]. However, the connection between the two was established via four venting pipes in which the gas flow rate was measured.

If one preferred a much shorter test, **PM15** could be used in which only 20 kg of melt were released within 1.35 sec. In this test the pressure only rose from the initial 5 bar to 5.16 bar.

If it would be desired to avoid the difficulty of the two volumes connected by venting pipes, test **PM18** could be chosen. In this test 15 kg of melt were released within 1.4 sec. The water was 26 K subcooled initially and the pressure rose from 2.3 bar to 2.9 bar. The vent pipes were closed.

Test **PM17** has a parallel test in FARO as well (L-31) but has the disadvantage of a high initial subcooling (104 K). It was performed with 15 kg of melt within a closed test vessel (like PM18) and the pressure rose from the initial 2.2 bar to almost 2.8 bar which is not much different from L-31: 2.2...2.7 bar. Maybe two effects compensated each other here: in FARO, the free board volume as well as the thermal energy of the melt were larger (by factors of about 2 and 4, respectively).

In all these tests the melt temperature was 2600 K which is clearly lower than the 3000...3050 K in the FARO tests. But this still gives about 300 K of melt superheat so that the premixing process should not be much affected by 'freezing'. (In FARO we have at best 200 K, which, at the higher absolute level, are lost much faster.) The large enough super heat may be a condition that is more important for the representativity of an experiment (for premixing and explosion) than the absolute temperature level or the exact nature of the melt.

It is an advantage of the PREMIX tests (like the FARO tests) that a whole series of experiments was performed at slightly varied conditions so that data from other tests may occasionally complete the picture.

While almost any of the late PREMIX tests (PM13...PM18) could be used for a calculation exercise, I suggest to use PM16, primarily because it has the more prototypical test conditions among the tests that have a parallel in the FARO tests.

3. Explosion experiment

In order to be always on the conservative side, a model of steam explosions must be able to describe the most violent explosions when conditions are encountered under which such explosions can occur. Therefore explosion models must be able to describe the strong explosions with **supercritical** pressures that have been observed with alumina in KROTOS as long as it isn't proven that this material has an unprototypical property to which it can entirely be attributed that it explodes so easily (?, see K-57 and ECO) and with such violence. Therefore, I suggest to choose one of the **alumina tests in KROTOS**.

In view of the difficulties that are caused by the squirting of an initial portion of the melt as seen in the last tests with visualization of the process, it would be desirable, to choose a test in which still a metal plate was used in the funnel. This would be e.g. the case in **K-28**. Unfortunately, in this test, the pressure very much exceeded the registration range of the instrumentation so that no good information about the peak pressures is available.

Test **K-29** is the last in which a tin disc was used. A strong spontaneous explosion occurred when the melt had penetrated to the bottom of the test tube, but only some of the pressure signals are informative.

Test **K-30** has unclear mixing conditions, a very strong spontaneous explosion and again several of the pressure traces go into saturation.

In all these cases the test data are not available in a form that would make them easy to use in a calculation exercise.

Among the further tests, **K-43** sticks out because it had a very strong explosion with much damage to the test tube, but the melt penetration data are quite irregular so that this test may be difficult to analyze.

Test **K-44**, performed with almost saturated water looks promising although the pressures are not extremely high. But they are well beyond the critical pressure and melt penetration is clearly monitored by the TC's. Also, the melt had penetrated to the bottom of the test tube at the time of triggering, so that the explosion clearly propagated the full length of the water column in upward direction.

Test **K-49** had a similarly strong explosion but the melt had only penetrated just beyond thermocouple K3 so that the interaction propagated only upward (only half the water column) while an almost constant pressure wave moved downward. The extremely high pressure of 127 MPa quoted for this experiment must come from the bottom pressure transducer K0, but that one obviously broke and didn't give reliable data.

In conclusion, test K-44 seems to be the best object of an explosion study.

In the final decision on this test case it would be an argument if people had already performed studies of the premixing phase (or the premixed state at the onset of the explosion) so that we could perhaps **define** an initial state for the explosion exercise instead of infecting it with the uncertainties of a premixing calculation. Test in which corresponding information is available might be preferable.

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OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in Npp's

IKE Contribution

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1. INTRODUCTION

In Task 1, relevant experiments for comparison calculations between codes shall be selected. In our view, the emphasis lies not in an additional validation exercise checking details of modelling. Emphasis should lie on the comparison of code results especially with respect to those effects from which major reductions of steam explosion loads are expected, i.e. void buildup under premixing, limitations to fine fragmentation from counter-processes in a pressure wave, explosion venting against pressure wave escalation.

If, e.g. with respect to void buildup under premixing, all codes would yield rapid void buildup to high values for mixture conditions in a realistic range, this would already mean a strong trend against energetic steam explosions. Existing modelling differences may then be of minor importance and validation concerns with respect to these differences, too. We consider it then as more important to check whether variations of conditions and of modelling yield lower voids and more critical mixtures, even whether physical mechanisms can be envisaged, which are not yet included in the codes but may prevent high voids. The question will then finally be whether the range of voiding spanned by different modelling for a given scenario is – together with other effects – sufficient to exclude critical loads from steam explosions.

Thus, in this sense, the comparison calculations between the codes shall mainly aim at elaborating the dominant effects and to obtain a generalised view on the restrictions to energetic explosions. This appears to be possible with respect to such overwhelming effects as the void buildup seems to be. At least, major differences and remaining questions should be elaborated (see the question under Task 2: Are effects that possibly reduce water depletion, such as subcooling, lateral water inflow, realistic drop surface temperatures, and reduced vapour formation from settled melt masses, adequately taken into account?). This has to be done for the premixing as well as for the explosion phase. In other words: The main task is to elaborate the modelling in a risk-oriented perspective. Of course, this means to perform calculations from the beginning in a relevant range, defined by realistic reactor scenarios. A relatively wide span may and should be considered for this, if it can be supported by realistic assumptions on processes, not just by constructing conditions which yield most energetic explosions. E.g., just assuming large premixtures of relatively dense mixtures with drop sizes of ~ 1 cm and little void would not be sufficient. In this sense, orientation at reactor conditions from the beginning should be considered, rather than envisaging already a detailed ranking of critical conditions, related to specific scenarios.

Experiments which yield sufficient answers on the key processes including a sufficient spectrum of conditions appear not to exist. Even with premixing, the question of relevant windows of conditions with lower void is not clear from the experiments. There appears to be a general rapid trend to high voids > 50 %, even with dilute mixtures (MAGICO results with spheres). However, e.g. transient jet breakup, increased pressures (< 20 bar) and higher subcooling may yield different results, at least for some time window. E.g., voids of < 20 % were estimated with experiment PREMIX-PM 17 (subcooling of 104 K at 0.22 MPa system pressure). In view of this lack of experiments covering the relevant ranges and yielding clear answers about major effects, it is again concluded that the method of analysis should not be just code validation in the usual sense with respect to specific experimental features, but the procedure already indicated above. Of course, the experiments should be chosen as appropriate as possible, i.e. direct or at least indirect control of key aspects should be possible. However, rather additional experiments should be calculated or at least taken into account for the specific checking of key effects than going into too much detailed aspects of comparison for the selected ones. The ranking of experiments to be calculated and the related arguments may yield first indications and further candidates for this procedure.

2. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

Due to depressurisation measures established generally within accident management, high pressure scenarios should be out of concern, i.e. system pressure in the scenarios for steam explosion considerations should be at least < 2 MPa, rather < 1 MPa, for in-vessel as well as ex-vessel cases.

A concern with in-vessel scenarios is a stratified explosion due to water injection above a melt pool in the lower head, either with corium or an overlying metal layer. The strength of explosions under such conditions is considered to be small due to limited mixing and strong venting effects restricting or excluding escalation processes. On the other hand, the RPV wall may be weakened significantly in the explosion range. In a first approach, parametric mixtures may be assumed here to check by explosion calculations (triggered thermal detonation wave along the surface) whether the venting effect is strong enough to prevent critical waves. With this respect, only explosion experiments are to be considered for this part. An emphasis would be on transverse venting, but venting effects may essentially be analysed by codes since essentially determined by wave dynamics. Specific explosion experiments on such venting effects are not known. Alternatively, integral experiments on stratified explosions could be considered, which also include mixing processes under feedback with wave motion at the interface. A specific model on this has been developed by CEA/ISPN in the frame of the EU-MFCI-project.

In view of limited resources in the project and the evaluation, that scenarios with melt falling into water should be more critical (and the above case can possibly also be covered by the parametric mixture and explosion calculations indicated), only this case is considered here. The in-vessel concern with this respect is a failure of the lower head due to steam explosions resulting from melt flows out of the core into remaining water in the lower plenum. Ex-vessel, again melt flows into an existing water pool, especially with deep water pools in respective retention concepts are considered as most critical with respect to possible damages to the cavity walls, RPV supports and containment penetrations. In all these cases, specific calculations are finally to be done for individual plants, especially with respect to specific geometrical configurations and resulting melt outflow, water pool and confinement conditions. I.e., the task is to provide the sufficiently validated codes for the load calculations. In the first steps, this should be done for idealised structures emphasising the key physical processes as discussed above.

Thus, flow of melt into water pools can be assumed as a generalised relevant scenario. Large melt pours may be considered as most critical in view of rapid contact and mixing of melt and coolant, before smaller interactions or strong voiding may prevent larger interactions. However, coarse mixing is impeded with large melt pours. Thus, the most rapid way to get large masses of melt in a distributed way in a water pool appears to be via various melt jets of appropriate diameter. This should yield most critical premixtures. But, a counteracting effect with denser mixtures remains by strong evaporation and void buildup. Thus, more dilute mixtures may even be more critical. Due to the various counter-effects, it makes no sense to define the most critical conditions in advance. It must be part of the code calculations and comparisons to detect the most critical conditions for which modelling differences may become relevant.

Since too thick melt jets would yield too little breakup and too thin jets too little melt flow into the water, critical sizes between, in a relevant range also from scenario considerations, are evaluated as ~ 5-20 cm in diameter. Overall flow rates could be further restricted by scenario analyses on outflow conditions.

Here, this should not be done from the beginning, or only in a rough way to exclude completely unrealistic assumptions (but such assumptions may even not yield the critical cases as indicated above). For a single melt jet, outflow velocities from a melt pool of ~ 1 m/s and velocities at water entrance up to ~ 10 m/s may be assumed, depending on the fall height. Under ex-vessel conditions remaining pressure differences between RPV and cavity may play some role in driving a jet, but not over most of the melt release time. With the restricted pressures assumed from depressurisation, not essentially higher velocities would result. Taking melt diameters of maximum 10 cm at water entrance would then yield maximum ~ 1 t/s flow rate of corium within a single jet.

Several jets may be possible, however. A melt pool of ~ 100 t could then be released to the water pool within 100 s assuming one jet or within 20 s (10 s) assuming 5 (10) simultaneous jets. Mass restrictions for explosive premixtures may be evaluated, taking into account that the falling time in water is maximum 2 – 10 s, depending on height of water pools, that settled material will participate to less degree, that spontaneous interactions are triggered during this latter time-scale (especially at bottom contact) if favourable conditions exist and that occurrence of several simultaneous jets within this time window may be limited.

Such considerations may be elaborated if critical conditions are detected from calculations for reactor scenarios. Here, the task is to choose most adequate experiments for the first step of comparison calculations. For this, already due to the limited experiments available, it is sufficient to choose a relevant jet diameter range, e.g. 3 – 10 cm, and a water entrance velocity of up to 10 m/s. Multiple jets would be of interest, especially with respect to possible interactions and overlapping of mixture regions. Otherwise, it would be simply a task of the codes to calculate extended mixtures based on the assumed typical behaviour of a single jet.

From the above considerations, it also results that long jet flows are to be expected. This is important also for the breakup process since it is concluded based on FARO and KROTOS experiments that small mass pours, i.e. short jets, will be governed by different breakup processes than long jets. This is actually considered as a major reason for the significant material differences obtained in KROTOS.

The inflow velocity may not only influence the size of premixtures, i.e. the total mass involved, but also the breakup behaviour and the void buildup in the mixture. The latter may be considered to be reduced by rapid penetration of melt into water and thus rapid buildup of mixtures. However, increased breakup can also be expected under such conditions (trend to thin film conditions) yielding higher void again. Again, the analysis of counter-effects is decisive to detect critical windows of conditions. If they are small, this renders less important both, the related detailed scenario analysis as well as the detailed modelling of respective processes.

Sufficient superheat of melt is a necessary condition for fragmentation. Certainly, crust formation is a criterion for too little superheat, which would hinder or prevent fine fragmentation, i.e. pressure escalations. At present, realistic superheats of corium are considered to lie 50-100 K above liquidus for release from the core in the RPV or up to 150 K for release from the RPV, i.e. temperatures of 3000 – 3100 K. The higher the superheat, the higher is the potential for explosions. Within this temperature range counter-effects of high temperatures favouring void buildup and vapour film stability are not considered as relevant.

Subcooling of water, on the one hand, damps explosion strength since part of heat is lost for heatup of water. On the other hand, the void buildup is reduced favouring triggering and pressure escalation. Further, lower vapour film stability favours triggering. However, this sensitivity yields spontaneous interactions rather preventing large premixing and thus explosions of large masses. Again, counter-effects necessitate parametric analyses to detect most critical windows. Medium subcooling may result in most critical explosions. Under in-vessel conditions rather saturated water is expected, ex-vessel, subcooled as well as saturated conditions can occur.

Triggering of explosions in premixtures strongly depends on local conditions. Restrictions can hardly be relied on. Local triggers may occur by entrapping water in melt, especially after contact with the bottom wall, whose strength will depend on details of such local events. Thus, within a realistic range, triggers shall be assumed in the analyses to check to what extent escalations are possible in given mixtures. With this respect, the ability of a mixture for spontaneous triggering is of less importance in these considerations.

3. RELEVANT PREMIXING AND INTEGRAL EXPERIMENTS

Sufficient data and defined conditions are first requirements for selection. With this respect there exist significant restrictions to all available experiments, due to the inherent complications and compromises between specific interest in processes and orientation at integral behaviour (e.g. including jet breakup with real melt vs. investigating mixing with spheres). However, some otherwise interesting experiments have been excluded here just because of rare data or relatively undefined conditions. E.g., for the FITS (Sandia) corium (with ca. 30 wt % steel) experiment MDC-2, yielding pressure peaks in water up to 100 MPa (50 MPa over > 13 ms), the inflow conditions of melt are unclear. Nevertheless, these results should be kept in mind for the parametric calculation.

A second direct criterion is given by the realistic choice of system pressure for relevant reactor scenarios. With this respect, high-pressure experiments in FARO should be excluded. However, at least concerning decision questions, the trend of data with system pressure as an interesting feature resulting from the FARO experiments should be kept in mind, also the basic results of the ISP 39 on the 5 MPa experiment FARO-L-14. While the pressure developments could essentially be calculated with most of the codes, significant differences were revealed in melt energy release, quenching rates and heat transfer surface areas obtained with the codes. I.e., breakup, heat transfer and distribution of heat in the water mostly have been significantly different in the modelling, partly with compensating effects concerning pressure development.

This way of examining code results, oriented at identifying differences and deficits with the general perspective to clarify and improve modelling, is insufficiently oriented at the goal to clarify (and develop sufficient tools for this) whether steam explosions under reactor scenarios may be critical. If, e.g., the differences do not change a possible major result of high void in relevant mixture regions, they may be not important. Thus, at this point it is important to look more in detail in the results (e.g. checking where the released heat goes to - superheat of steam, surrounding water - and where the steam goes, especially what voids are established) orientation at details of experimental results.

A further important decision criterion concerns the amount of melt released, melt jet diameters and the water mass and depth. Jet diameters in the relevant range of some centimetres are chosen in several experiments. Water depths of at least 50 cm, better > 1 m are also usually established and appear appropriate. In view of having an appropriate length in water for breakup, a certain relation of water depth to jet diameter should be taken, oriented at relevant reactor scales (in-vessel: depth/diameter ~ 2 m/0.1 m = 20, ex-vessel, deep pool ~ 8 m/0.1 m = 80). L/D-ratios ~ 20 – 50 are also obtained from specific jet breakup experiments. Diameters of water pools should also not be too restricted to avoid (untypical, in view of reactor scenarios) pressurisation and level swell as well as expulsion of melt due to lateral constraint. For this, pool diameter/jet diameter ratios should at least be > 5 (in KROTOS experiments such effects have been avoided for corium jets of ~ 3 cm diameter by choice of 20 cm inner vessel diameter instead of the earlier of 9.5 cm). This also appears to be guaranteed in most cases. The melt mass should be large enough to get a long jet for establishing the breakup mechanisms considered to be relevant under reactor scenarios, especially to avoid dominance of leading edge effects, either of large disturbances or of specific breakup under thin film boiling conditions. Both effects may even be pronounced by high water entrance velocities. Especially due to the possibility of the latter effects, i.e. due to relatively low mass and high entrance velocities, the KROTOS experiments are no primary candidate as reference experiment for the premixing analyses. Nevertheless, since KROTOS experiments are important for explosions analyses (see following chapter), considerations about the premixing behaviour will have to be done in this frame, there also with respect to the material effects of Al_2O_3 vs. Corium.

With the ALPHA experiments of JAERI, applying ~ 20 kg of alumina (thermite), observations seem to be connected with the dispersion device. This yields – to some extent – a direct detection of counteracting effects on explosions connected with pre-breakup of melt. Increased initial dispersion may be considered as favourable for explosions. But, less melt dispersion concluded for STX019 compared with STX020 and STX021 yielded a stronger explosion. This may be due to smaller void. However, pressure developments are not given in major publications and thus the conclusions from conversion ratios remain unclear. Also the conditions are rather unclear, especially the effect of the dispersion device (concerning less dispersion in STX019 local failure of the dispersion device is considered as a possible reason). Evaluation of melt structure at the entry into water was not possible for these experiments with dispersion device. Thus, although containing some interesting indications, the experiments appear not be particularly appropriate for the analyses, neither for the explosion nor for the premixing phase. The interesting aspects, especially effects of the dispersion device and explosions (but: strength? pressures? – wave propagation velocity given) occurring at relatively high voids of ~ 40 - 50 % in STX019 (detected from visual observations of the mixing zone and level swell), should nevertheless be taken into account within the analyses. It may also be of interest that these relatively high voids are obtained at strong water subcooling: water temperatures of 281 – 295 K at 0.1 MPa system pressure. Since e.g. pressure histories in the water have been recorded in principle, there may also exist additional data, not given in the literature which was available.

Compared to this, the PREMIX experiments of FZK, performed with ~ 15 – 60 kg of alumina / thermite melt, mainly close to saturation conditions appear to be more appropriate for the premixing analyses, due to the rather defined conditions and detailed results. Release conditions are defined with melt jet releases of ~ 5 cm diameter, i.e. in the relevant range. Measurements of pressure in the water and the overlying gas, of steam volume flow rates out of the vessel and of water level have been performed. Evaluations of global parts of steam, melt and liquid water in the pool have been done, based on this. Further, local void measurements in the mixture have been performed. Visualisation yielded the penetration history of the jet as well as the development of the mixture region. Debris has been analysed.

Mostly, PREMIX experiments have been performed at 0.1 MPa system pressure with saturated water. No explosions occurred, besides in PREMIX-PM 11 where a triple nozzle was applied producing 3 jets. However, the maximum pressure of the spontaneous explosion was only 3 MPa and the analysis of mixture behaviour rather indicates local conditions favourable for triggering rather than specific features in general.

PREMIX experiments with subcooling have also been performed, especially PREMIX-PM 18 and PM 17 at 0.22 MPa system pressure and significant subcooling of 26 K and 104 K, respectively. In contrast to KROTOS experiments with subcooling no spontaneous explosions occurred. System pressure and temperature conditions in PREMIX-PM 17 were nearly the same as in KROTOS-43 (Al_2O_3-experiment) where a strong spontaneous explosion occurred. Voids were small in both cases, the higher values with PREMIX-PM 17 understandable from larger mass. However, larger part of debris was found as a cake in PREMIX-PM 17 indicating little breakup. This result and the rather narrow jet flow in PREMIX-PM 17 video pictures remind of FARO-L-29, with 0.2 MPa system pressure and 97 K subcooling where only little breakup occurred, in contrast to FARO-L-31 at similar conditions, yielding complete breakup comparable to previous FARO experiments, seemingly also to FARO-L-28 (for which the debris analysis is missing) with 0.5 MPa and saturation. An explanation may be, that at lower entrance velocities in water and with longer jet in PREMIX-PM 17, compared to KROTOS-43, stripping under thin film conditions with high subcooling is not effective. If this would have prevented stripping also in FARO-L-29 in contrast to FARO-L-31, high subcooling would provide a sensitive range. However, less superheat in FARO-L-29 than in FARO-L-31 may also be an explanation. Such large subcooling is also not considered as very relevant with respect to reactor conditions, neither for in-vessel nor for ex-vessel conditions.

Thus, PREMIX-PM 17 cannot be taken for the analyses because of the unclear results at high subcooling. But also FARO-L-31 and FARO-L-33 appear then questionable, anyway with respect to reactor conditions. On the other hand, there is some interest in the subcooling case because of reduced void and thus possibly increased steam explosion potential. For the premixing phase the detection of ranges with reduced void is an aim of investigations. Further, since the obtained debris in FARO-L-31 looks rather similar to that in FARO-L-28, it may be assumed that, in view of higher superheat (and the higher corium temperatures than with PREMIX alumina cases) and long jets, thin film stripping is not important in FARO-L-31. The same may be valid for FARO-L-33.

Since in FARO-L-33 triggering was applied, this is a candidate for the integral experiment to be selected, including premixing and explosion phases. Certainly another essential argument, as compared to PREMIX experiments, is the prototypic melt material. However, no debris evaluation is available for FARO-L-33. From photographs, larger parts of cake material may be concluded. This is in contrast to FARO-L-31 (similar subcooling of 124 K at higher system pressure of 0.4 MPa). But, in FARO-L-33 triggering was applied after 40 kg of melt had been released. This should have produced some amount of small fragments, but may also have resulted in voided regions yielding less breakup for subsequent melt flow. Then, the debris results are obscured with respect to the original premixing behaviour. From this, FARO-L-33 may be taken for the integral analyses but is problematic for the comparison calculations specific on premixing. FARO-L-31 is then more appropriate for the latter. Questioning the relevance of the high subcooling for reactor conditions and the possibly special effects on breakup in this range, even earlier saturation experiments FARO-L-28, L-27 and L-24 at 0.5 MPa system pressure may be preferred. The disadvantage of FARO-L-28 is the missing debris analysis (although seemingly complete breakup, similar to FARO-L-31), while the disadvantages of

FARO-L-27 and L-24 are that visual jet characterisation has only been done after these experiments, the jets with 10 cm diameter in these experiments and water depth of 2 m yield in contrast to 5 cm jet diameter and water depth of 1.5 m in FARO-L-28 (as well as in the subsequent experiments) much shorter jets and jet flows as well as not complete breakup up to the bottom. Complete breakup facilitates checking of breakup modelling.

Proposing, nevertheless, FARO-L-31 for the analyses is done with pre-caution, that switching to one of the other experiments, preferably FARO-L-28 should be decided during the analyses if the adverse arguments have to be considered as too strong. Further, along the above discussion lines, the results of the other experiments should in any case be included at least in considerations performed in the analyses related to the chosen experiment. Benchmark analyses which have been performed should be re-considered concerning open questions. FARO-L-27 benchmark was cancelled due to off-centre jet discharge in the test, thus FARO-L-27 should also be excluded from the analyses. Thus, the FARO-L-28 benchmark is of special importance. FARO-L-28 has been considered to be very appropriate with several respects, e.g. prolonged discharged, quasi-stable period for injection flow, pressurisation, quenching rate, lower importance of injected mass, centred jet, no clape influence, smaller influence of H_2. Further, it is then the first relevant experiment in the FAT vessel and jet characterisation has been performed. In the benchmark exercise, the energy release and heat transfer surface (i.e. breakup) was by part of the participants strongly underestimated, while void fraction and level swell have rather been overestimated.

In view of the detailed experimental evaluations in the PREMIX experiments, including visualisation of jet penetration and mixing zone development in the water, and to get some perspective about effects of different melt material, a PREMIX experiment should also be chosen for the analyses. PREMIX-PM 17 has already been excluded due to specific features and uncertainties, although this was considered as a parallel experiment to FARO-L-31 (and thus also to FARO-L-33, concerning subcooling). PREMIX-PM 18 may be of interest because of the moderate subcooling. But the melt mass was only 14.6 kg. PREMIX-PM 16 has been considered as a parallel experiment to FARO-L-28, concerning pool geometry, system pressure and water temperatures, but especially with respect to an elongated pour (the choice of 60 kg melt mass was considered to yield a similar energy input as in FARO-L-28). A disadvantage in this experiment may be the significant cake part of debris with respect to clear checking of breakup features. PREMIX-PM 15 with only 23 kg melt yielded rather complete breakup PREMIX-PM 12 – PM 14 are interesting because of choice of the same conditions as reproducibility test. Again, the trends with all these experiments should be kept in mind for the analyses. For direct selection, however, preference is given to PREMIX-PM 16, especially due to the long pour conditions and parallelisation to FARO-L-28 (in spite of the above questioning).

Further, the new TROI experiments have to be considered. They apply prototypic material (UO_2-ZrO_2) as in FARO and KROTOS. TROI-13 has become of major interest because it yielded the strongest of three spontaneous explosions obtained. With only 7.7 kg released mass and 2 – 3 cm diameter of melt jet, it is rather comparable to KROTOS explosion tests than appropriate for mixing analyses. Breakup features may be of interest since a jet of ~ 2 cm diameter entering water has clearly been visualised. An advantage is the larger diameter of water vessel of 60 cm compared to 20 cm in KROTOS. The major result is a spontaneous explosion with a pressure peak of 6 MPa (4 MPa for $\leq$ 1 ms) has been obtained while in KROTOS experiments propagating pressure waves only were produced by external triggering (with comparable pressure magnitude but only about twice of the mechanical energy of the trigger itself). In FARO-L-33, also a strong trigger was applied yielding a pressure increase from 5 to 10 MPa from bottom to top, but over most of the vessel height rather maintenance of the trigger strength. Nevertheless, by comparison with the trigger in pure water significant effects can be seen in the FARO and KROTOS cases. Considering critical explosion strengths in reactor scenarios all these events appear not to be important.

The new ECO series of experiments with alumina melt at FZK, which continue the PREMIX experiments and additionally include the explosion phase, appear not yet ready for closer consideration based on available results. Only small masses of melt (< 6 kg) have been applied up to now and triggered interactions were relatively weak, besides ECO-04 (maximum pressure of about 28 MPa), for which detailed analyses are not yet available.

As a summary for premixing, it is proposed to select **FARO-L-33** for the integral analyses, but keeping in consideration during the analyses especially FARO-L-31 and FARO-L-28. As further, specific experiment for the premixing phase, **PREMIX-PM 16** is then proposed, also keeping in mind the results of other PREMIX experiments, especially PREMIX-PM 12 – PM 14, PREMIX-PM 15 and PREMIX-PM 18. Since the main emphasis of the investigations should lie on the possibilities of establishing most critical premixtures with sufficiently high melt content and not too large void, and the adequacy of code descriptions with this respect, it may also be important to take into account results of basic experiments as MAGICO and QUEOS for clarification.

4. RELEVANT EXPLOSION EXPERIMENTS

With respect to specific clarification on the explosion phase, all available corium experiments with sufficiently defined conditions appear to be of less importance, just due to the relatively low explosion strengths obtained. The FITS MCD-2 experiment for which a very strong pressure pulse has been observed, even from a spontaneous explosion, seems to be poorly documented. The best experiments with respect to explosion strength and clearly detected propagating or escalating waves appear to be the KROTOS experiments with Al_2O_3. Nevertheless, interactions with prototypic material should also be analysed to keep the perspective of understanding material differences or effects of specific experimental features and thus to conclude on reactor scenarios. For this, the integral experiment FARO-L-33 has already been chosen. But again, specific experiments as KROTOS experiments with corium (e.g. K-52 or KT-2) as well as TROI experiments and FITS-MDC-2 should be kept in mind. The spontaneous interactions in TROI experiments up to now are however problematic with respect to code validation. From ECO experiments with triggered interactions sufficient results are not yet available. However, further progress in TROI and ECO experiments should be observed.

For the specific explosion analyses, however, the strongest events available with best experimental evaluation should be chosen, i.e. alumina test of KROTOS. To consider these strong interactions is a necessary condition for being able to analyse reasons for weaker interactions and especially the potential for reduction effects under realistic reactor scenarios. Several experiments could be selected from the KROTOS series. Here, **KROTOS-44** is proposed in which clearly an upwards propagating and escalating pressure wave, initiated by the trigger, has been detected. Stronger escalations have been obtained in other experiments. E.g. in KROTOS-28 a very rapid escalation was obtained to a pressure level where the pressure transducers failed. Thus, comparison is restricted. In other experiments with stronger escalations, spontaneous interactions occurred at some medium elevation with pressure waves and escalations towards top and bottom. This complicates the analyses. Thus, KROTOS-44 appears to be a good choice, with strong enough pressure waves running from bottom to top and escalating.

5. SUMMARY

The following experiments have been selected as proposal for the code calculations:

1) FARO-L-33 as integral experiment for premixing as well as explosion phases.
2) PREMIX-PM 16 as specific premixing experiment.
3) KROTOS-44 as specific explosion experiment.

In addition, it is emphasised that accompanying analyses on these experiments should take into account especially the following experiments:

For premixing: FARO-L-28 and -L-31,
PREMIX-PM 12 – 14, PM 15 and PM 18,
FARO-L-29 and PREMIX-PM 17 are of interest
with respect to the special behaviour,
continued ECO experiments to be observed.

For explosion: Other KROTOS experiments with alumina and corium,
TROI experiments (TROI-13) , FITS-MDC-2, ECO experiments.

Subsequently, results of the above considerations are – as far as possible – structured according to the required form.

6. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

Classification and ranking has been done with respect to

- most critical cases
- realistic reactor conditions
-

i.e. which conditions yield strong energetic explosions and are compatible with realistic reactor scenarios. For the choice of relevant experiments it has been tried to first restrict the range of conditions to a useful subset according to the above criteria and then to select the experiments which are most critical with this respect.

6.1. Melt temperature: superheat

A sufficient superheat of the melt is an absolute precondition for getting vapour explosions, due to the coarse and especially fine fragmentation requirements. Melt pools in reactor scenarios are considered to yield superheats of ~ 50 – 150 K, i.e. corium temperatures above liquidus, 2900 K – 3000 K, taking 2850 K for a corium liquidus (80 wt% UO_2 / 20 wt% ZrO_2). For the investigations rather somewhat higher superheats should be considered, since emphasis is to be laid on other restricting effects to explosions than solidification or effects of increased viscosity. It is problematic to rely on such effects related to limited melt superheat since higher superheats in reactor scenarios can presently not be excluded, especially if metallic melt parts are involved. Crust formation should be considered (as an effect preventing explosions and likewise favouring formation of coolable particulate debris), but not in the first line.

6.2. Melt flow into water: mode, flow rate

Some splitting up of melt flow to the lower plenum of the RPV as well as to the cavity is considered as most critical, rather than large streams or floods. Relevant scenarios in this respect are single or multiple releases as jets of diameters ~ 5 – 15 cm. Flow rates in one jet of maximum ~ 1 t/s may be considered, yielding in several jets releases up to ~ 100 t in 10 –20 s, at maximum.

Higher flow rates with single jets increase the mass deposited within a certain time in the water pool and thus the potential to get a mixture with larger melt content. On the other hand, void buildup as counter-effect against explosivity may then be emphasised. Thicker jets will reduce this effect but also the possibility of mixing due to reduced breakup.

If not interacting, multiple jets will simply extend the size of the mixture, i.e. increase escalation potential and participating mass. If overlapping, this is equivalent to increased mass input in certain regions with the same counter-effects as indicated above.

Concerning realistic reactor scenarios, lateral melt releases from the top region of melt pools, under in- and ex-vessel releases, should yield lower melt flow rates than bottom releases. At present, also the latter case cannot be fully excluded. But, accumulation of melt in the core up to significant amounts may then be questioned. Simultaneous occurrence of multiple jets within a relatively small time range of maximum 10 – 20 s may also be questioned, especially for lateral releases.

6.3. Duration of melt flow: released mass, jet length

The duration of melt flow, i.e. the total released mass, is important with respect to changes of conditions in time (e.g. void buildup changes the conditions for subsequent inflow phases) or establishment of quasi-stable inflow conditions. For relevant reactor scenarios, long jet flows are expected and should yield most critical explosion conditions. Thus, several times the jet breakup length or even water pool depth should be considered as relevant. With a jet length L / jet diameter D ratio of ~ 30 and D = 0.1 m (0.05 m), this would mean a required jet length » 3 m (1.5 m), i.e. a corium melt mass of » 200 kg (25 kg) in experiments with corium.

Significantly smaller flow lengths and corresponding masses may even not yield established breakup under "thick" vapour film or multiphase region conditions and must then be considered not relevant for the reactor scenarios.

6.4. Water depth and mass

A sufficient water depth is necessary for mixing processes and establishment of sufficiently large premixtures to yield strong explosions. Water depths of 1 – 2 m may be assumed for in-vessel scenarios, up to 10 m for specific ex-vessel scenarios with deep water pools as retention measure.

The width of water pools may restrict mixing and even melt inflow in some experiments with small diameter vessels, but should not be of significant influence in this respect for reactor scenarios. However, influences have to be considered concerning explosion venting possibilities.

6.5. Melt composition: corium, metal part

Relevant melt compositions in reactor scenarios comprise a relatively wide spectrum depending on reactor type and core melt development. E.g., with BWR much more metallic parts are involved. With respect to PWR and the emphasis on in- and ex-vessel scenarios with melt flow into water, some limitations may be deduced, in the direction of UO_2/ZrO_2 based compositions with some metallic parts.

However, also from the side of analysis of present knowledge about material effects (see previous chapters), no clear conclusions about specific, overall valid corium effects on explosion strength can be drawn. Thus, for the investigations in SERENA, certainly corium experiments and possible effects must be a concern, but not a major, exclusive reference. In this sense, requirements of prototypic material are reduced. Exploring of possible effects is considered as important and may change this ranking.

Metallic parts may yield H_2-production by oxidation as an additional systematic effect, as e.g. seen in the stronger jet breakup in FARO-L-11 involving 4 wt% unoxidized Zr. However, again this effect should not be relied on but rather be included in some variation of breakup in the SERENA analyses.

6.6. Water temperature: saturation, subcooling

In in-vessel scenarios, rather saturation conditions are to be assumed, in spite of special conditions with intermediate cold water injection. Ex-vessel conditions may be both saturation and moderate subcooling.

Concerning the effect on explosions, subcooling reduces void and thus favours stronger explosions, but counter-effects may result at high subcooling due to effects on breakup (see previous chapters) and in general due to the heat part required for water heatup.

Triggering is favoured by subcooled conditions but should also not relied on here. With assumed triggers, saturation conditions may even yield stronger explosions.

6.7. Entrance velocity of melt into water

As outlined under I.3, an increased inflow velocity would mean to promote mixing of larger masses. A counter-effect may be stronger voiding. This may be increased if thin film boiling conditions would be produced and by this breakup would be enforced. Counter-effects must be explored to analyse the possibility of critical conditions.

Entrance velocities up to ~ 10 m/s appear to be possible in reactor scenarios.

6.8. Trigger

Triggers in reactor scenarios may be due to impact of material at walls and especially entrapment of water in melt or at walls (preferably at bottom). However, according to the above argumentation special considerations on triggers should not be done in SERENA. Possible needs of limitations to assumed triggers are to be dealt with during the investigations.

With respect to performance and interpretation of code calculations, spontaneous interactions pose difficulties due to undefined conditions. Therefore, experiments with defined location and strength of triggers are to be preferred.

6.9. System pressure

System pressure yields a first direct criterion since high-pressure conditions can meanwhile practically be excluded due to depressurisation measures. System pressure may be important with respect to the possibility of strong explosions since suppression of such explosions by high system pressure is assumed mainly due to triggering restrictions. Although such restrictions are considered valid for spontaneous explosions, triggering possibilities are not fully excluded as shown by several experiments.

A range of system pressures up to 20 bar, rather < 10 bar is considered as relevant, already from reactor scenario considerations.

Nevertheless, experiments and calculation cases with higher pressures may be of interest for the investigations with respect to understanding trends and effects.

7. RELEVANT PREMIXING EXPERIMENTS

Addressing reactor conditions the best must be taken with care. Emphasis must lie on understanding and sufficient modelling of relevant conditions. This may imply that checking is favourable even with less prototypic conditions, e.g. not prototypic material. As outlined in the previous chapters it is important to keep relations to various experimental conditions and results rather than relying just on one selected, orientating analyses just at this. Based on the previous chapters, only short outlines are given here.

7.1. FARO-L-33 as integral experiment for premixing and explosion phases

7.1.1. Description of experiment

Main characterisation in view of selection:

- 80 wt% UO_2 – 20 wt% ZrO_2 corium melt,
- mass released up to triggered interaction: 40 kg,
  total mass released: 40 kg,
- melt temperature: 3073 K (superheat: 223 K),
- subcooling of water: 124 K,
- system pressure: 0.41 MPa,

- release diameter: 0.05 m,
- gravity release; melt entrance velocity in water: 4,5 m/s,
- water depth: 1.62 m,
- FAT vessel (closed).

Summary of results:

- pressure development,
- temperatures in gas and water,
- melt leading edge progression from thermocouple signals,
- water (mixture) level,
- propagation of energetic event after triggering,
- temperatures at bottom plate,
- debris: only visually.

References:

- FARO Test L-33 Quick Look Report, Technical Note No. I.00.111.
- FARO LWR Programme Test L-33 Data Report, Technical Note No. I.00.124.

7.1.2. Relevance to reactor conditions

Integral behaviour with relevant mass of corium of 40 kg at sufficient superheat up to and including triggering/explosion effects. Effects of continued release up to 100 kg.

7.1.3. Level of characterisation of initial and boundary conditions

Essential data given

7.1.4. Quality of data

- missing data: steam production, void buildup
- quantitative analysis, in principal obscured concerning mixing due to the explosion part and the subsequent hereby modified processes.
- quality of data in general to be further checked during analyses.

7.1.5. Unresolved discrepancies with previous calculations

No previous comparison calculations with different codes

7.2. PREMIX-PM 16: Selected specific for premixing

7.2.1. Description of experiment

Main characterisation in view of selection:

- 90 wt% Al_2O_3 – 10 wt% iron melt
- mass released: 60 kg
- melt temperature: 2600 K (superheat: 286 K)
- subcooling of water: 5 K
- system pressure: 0.5 MPa
- release diameter: 0.048 m

- melt release controlled by pressure; entrance velocity in water: 1.9 m/s - 2,5 m/s
- water depth: 1.33 m; vessel diameter 0.69 m

Summary of results:

- pressure in gas and water
- temperatures in gas and water
- water level
- steam flow rate and integrated steam volume
- quenching rate calculated from steam production rate and integrated energy transferred
- development of mixing zone in water (from visualisation)
- progression of leading edge of melt yielding jet breakup length
- local steam and wtaer measurements with void probes at selected times
- sieve analysis of debris

References:

- Kaiser A., W. Schütz, H. Will: PREMIX Experiments PM 12 - PM 18 to investigate the Mixing of a Hot Melt with Water, FZKA 6380, July 2001.

7.2.2. Relevance to reactor conditions

Detailed data to check premixing behaviour and models, especially with respect to the major questions of breakup and void-buildup. Long pour / large mass. Experiment considered as parallel experiment to FARO-L-28 (benchmark calculations have been performed for FARO-L-28).

7.2.3. Level of characterisation of initial and boundary conditions

Essential data given

7.2.4. Quality of data

- Relatively detailed data.
- Quality of data in general to be further checked during analyses.

7.2.5. Unresolved discrepancies with previous calculations

Emphasis on melt breakup and void buildup as compared to FARO-L-28 (benchmark: large discrepancies)

7.3. FARO-L-31

7.3.1. Description of experiment

Main characterisation in view of selection:

- 80 wt% UO_2 – 20 wt% ZrO_2 corium melt,
- mass released: 92 kg,
- melt temperature: 2990 K (superheat: 140 K),
- subcooling of water: 106 K,

- system pressure: 0.22 MPa,
- release diameter: 0.05 m,
- gravity release; melt entrance velocity in water: 4.5 m/s,
- water depth: 1.45 m,
- FAT vessel (closed).

Summary of results:

- pressure development,
- temperatures in gas and water,
- melt leading edge progression from thermocouple signals,
- water (mixture) level,
- quenching rate and maximum average void fraction,
- temperatures at bottom plate,
- debris analysis.

References:

- A. Annunziato, C. Addabbo, D. Magallon: FARO test L-31 Quick Look Report, Technical Note No. I.99.193, Dec. 1999.
- R. Silvestri, D. Magallon: FARO LWR Programme Test L-31 Data Report, Technical Note No. I.99.100, INV-MFCI(99)-D035.

7.3.2. Relevance to reactor conditions

Experiment with water at subcooling comparable to FARO-L-33 (although lower system pressure). No triggering, no explosion, i.e. unaffected premixing behaviour. To be analysed concerning effects on breakup and in perspective of lower voids in mixing. Comparison with FARO-L-28 results especially with this respect.

7.3.3. Level of characterisation of initial and boundary conditions

Essential data given

7.3.4. Quality of data

- Missing data: steam production.
- Quality of data in general to be further checked during analyses.

7.3.5. Unresolved discrepancies with previous calculations

Status not available, perspective as given under II.3.b.

8. RELEVANT EXPLOSION EXPERIMENTS

Addressing reactor conditions the best must be taken with care. Emphasis must lie on understanding and sufficient modelling of relevant conditions. This may imply that checking is favourable even with less prototypic conditions, e.g. not prototypic material. As outlined in the previous chapters it is important to keep relations to various experimental conditions and results rather than relying just on one selected, orientating analyses just at this. Based on the previous chapters, only short outlines are given here.

8.1. FARO-L-33 as integral experiment for premixing and explosion phases

See II.1.

8.2. KROTOS-44: selected specific for explosion

8.2.1. Description of experiment

Main characterisation in view of selection:

- Al_2O_3 melt,
- mass released 1.5 kg,
- melt temperature: 2673 K (superheat: 359 K),
- subcooling of water: 10 K,
- system pressure: 0.1 MPa,
- release diameter: 0.05 m,
- water depth: ~ 1 m,
- inner diameter of test section: 0.2 m.

Summary of results:

- melt penetration from thermocouple signals,
- mixture level swell yielding average void,
- well characterised pressure wave propagation and escalation from bottom to top due to trigger of defined strength,
- debris analysis.

References:

- I. Huhtiniemi, H. Hohmann, R. Faraoni, M. Field, R. Gambaretti and K. Klein: KROTOS 38 to KROTOS 44: Data Report, Technical Note No. I.96.37, Joint Research Centre Ispra, February 1996.

8.2.2. Relevance to reactor conditions

Strong explosion (propagation and escalation) to be taken as a reference. Codes must be able to calculate this in order to check reduction effects under realistic scenario conditions. Specific features in this respect: lateral confinement yields 1D features promoting escalation; thus smaller mass with less void sufficient to provide strong escalation.

8.2.3. Level of characterisation of initial and boundary conditions

- Data on entrance conditions at water surface are missing. To be deduced from separate specific tests on velocity development up to melt / water surface contact and visualisation of mixing behaviour after entrance.
- Mixing conditions to be evaluated from entrance evaluations and mixture level swell concerning void development and drop sizes.
- Local distribution of mixture conditions at time of triggering to be evaluated based on calculations and available experimental data (melt penetration, level swell, pressure).

8.2.4. Quality of data

- quality of data in general to be further checked during analyses.

8.2.5. Unresolved discrepancies with previous calculations

Main perspective: elaborate dependence of pressure wave propagation and escalation on mixture data, especially drop sizes and void, and key modelling aspects (fine fragmentation, non-homogeneous water heatup).

Further:

- Analyses on possible behaviour with similar premixing for corium
- application for same mixture but stronger venting (e.g. larger vessel).

JAERI Contribution

A Proposal of JAERI for

SERENA Task 1

Identification of FCI conditions

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I. Relevant conditions for Energetic FCI in NPPs

In Japan, 23 PWRs, 15 BWRs with Mk-I CV, 11 BWRs with Mk-II CV and 2 ABWRs are in operation as of October 2000. Among these reactor types, ex-vessel FCIs have importance from the risk viewpoint in the severe accident sequences relevant to BWRs with Mk-II CV and PWRs.

Two specific cases of conditions are provided for BWR Mk-II and PWR in the following sections.

I.1 BWR Mk-II wet well (1100MWe)

BWR Mk-II plants have a wet well (suppression chamber) below the reactor vessel which contains a large amount of subcooled water. The wet well is separated from the = dry well by pedestal floor made of reinforced concrete. When molten core is ejected from the reactor vessel due to lower head failure, it first attacks the pedestal floor. The molten core finally drops into the wet well penetrating the pedestal floor, contacts with subcooled water and causes an FCI.

Even if the FCI is not energetic enough to cause the containment vessel failure by its dynamic loads, only a rapid steam generation may cause the containment failure due to over-pressure, because the containment volume is not very large and the suppression function of the wet well is lost by the melt through of the pedestal floor in this accident sequence.

Most significant accident sequences relevant to FCIs in the wet well are:
⑩TQUV -- A transient initiated by loss of feed water. Failures of both high and low pressure ECCS, while successful in manual depressurization, and
⑩TQUW, TQUV1W -- A transient initiated by loss of feed water. Failures of high pressure injection and containment heat removal, while successful in low pressure injection and automatic depressurization,
according to an evaluation of containment failure frequencies in BWR severe accidents performed at JAERI based on Accident Progression Stage Event Tree (APSET) method(1).

The accident progression analyses by an integrated severe accident code THALES-2 developed at JAERI(2) indicated that TQUV has lower containment pressure and subcooled suppression pool; both conditions suitable for the energetic FCI to occur. On the other hand, TQUW and TQUV1W have relatively high containment pressure and the suppression pool at nearly saturation temperature. Therefore, from the FCI view point, the TQUV is considered to be the most important.

Relevant thermohydraulic conditions were deduced mainly from the analysis result by THALES-2 code. Other sources (3,4,5,6) and calculations on TQUX sequence (similar to TQUV but reactor depressurization in failure) with MELCOR 1.8.3 performed at JAERI was referred for the molten core composition. The initial temperature of the molten core was assumed to be slightly higher than the liquidus temperature.

❿Maximum molten core mass and composition

total: 270 t
wt%: 55-- UO_2, 5-- ZrO_2, 25-- Zr, 15-- Steel
⑩Molten core temperature: 2700 K (superheat <50K)
⑩Molten core ejection hole diameter: 0.5 to 1 m (pedestal floor ablation)
⑩Fall height from the pedestal floor to the water surface: 4.5 m
⑩Water pool depth: 8.2 m
⑩Water pool diameter: 6.3 m (central part of the wet well)
⑩Water temperature: 355 K (Tsat = 426 K)
⑩System pressure: 0.52 MPa
⑩Free volume: 9500 m^3 (containment gas phase)
⑩Cover gas temperature: 355 K
⑩Cover gas composition (mol%): 75-- steam, 21-- N_2, 4-- H_2

References
1) N. Watanabe et al., A new modelling approach for containment event tree construction -- Accident progression Stage Event Tree method, 2nd International Conference on Containment Design and Operation, Toronto, 1990.
2) J. Ishikawa et al., Systematic source term analysis for level 3 PSA of a BWR with Mark-II containment with THALES-2 code, 10th International Conference on Nuclear Engineering (ICONE-10), Hyatt Regency Crystal City, 2002.
3) Kashiwazaki-Kariwa Unit-3 construction plan approval application documents (Publicly disseminated version, in Japanese).
4) Institute of Nuclear Safety, Nuclear Power Engineering Corporation (NUPEC/INS), Report on a level-2 PSA of 1100MWe class BWR plant, INS/M93-09, 1994 (in Japanese).
5) M. Kato and H. Nagasaka, COTELS project (2): fuel coolant interaction tests under ex-vessel conditions, OECD Workshop on Ex-Vessel Debris Coolability, Karlsruhe, Germany (FZKA 6475), 293--300, 1999.
6) M. T. Farmer et al., Liquidus/solidus and Zr solubility measurements for PWR and BWR core melt compositions, OECD Workshop on Ex-Vessel Debris Coolability, Karlsruhe, Germany (FZKA 6475), 380--393, 1999.

I.2 PWR reactor cavity (1100MWe)

In PWRs, a deep water pool can be formed in the reactor cavity due to coolant discharge during LOCA and containment spray, or by intentional flooding as an accident management measure. Therefore, in case molten core is ejected from the pressure vessel bottom, it is likely to drop into a deep water pool in the cavity causing an FCI.

According to a PSA performed by NUPEC/INS on a PWR with 4 loops(1), the plant damage state which has the highest contribution in the core damage frequency is the one called SLC, which is a small break LOCA with failure of both high and low pressure injection systems at re-circulation stage. Another plant damage state is SEC, which is similar to SLC, while low pressure injection system is in failure and the core damage occurs earlier than in SLC. These two are the small break LOCA cases with containment spray working, so that the reactor cavity is likely to be flooded. Representative sequences of these categories, SLC and SEC, are S2H and S2D, respectively.

Thermohydraulic data relevant to the FCI condition was taken from MELCOR 1.8.2 analysis on S2H sequence in Ref.(1) and MELCOR 1.8.5 analysis performed at JAERI on S2D sequence.

⑩Maximum molten core mass and composition
  total: 109 t
  wt%: 75-- UO_2, 6-- ZrO_2, 10-- Zr, 9-- Steel
  (for S2D, more amount of Zr should be oxidized in S2H)
⑩Molten core temperature: 2700 to 2800 K (superheat <50K)
⑩Molten core ejection hole diameter: 0.05 to 1 m (penetration failure or large scale failure)
⑩Fall height from the pedestal floor to the water surface: 0 m
⑩Water pool depth: 5.0 m
⑩Water pool diameter: 6.0 m
⑩Water temperature: 350 to 390 K (Tsat = 393 K)
  (MELCOR calculations indicated nearly saturation temperature. A certain subcool range is included here considering intentional subcool water flooding as AM measures and uncertainty in heat transfer models in MELCOR predictions.)
⑩System pressure: 0.20 MPa
⑩Free volume: 737000 m^3 (containment gas phase)
⑩Cover gas temperature: 390 K
⑩Cover gas composition(mol%): 65-- air, 35-- steam

References

1) Institute of Nuclear Safety, Nuclear Power Engineering Corporation (NUPEC/INS), Report on a level-2 PSA of 1100MWe class PWR plant, INS/M93-08, 1994 (in Japanese).

II. Relevant Premixing Experiments

II.1.a FARO L-28, JRC-Ispra, EU

Corium jet breakup and mixing in a saturation temperature water pool at 0.5MPa with a long jet pour period.

- Melt mass: 175 kg
- Melt composition: 80wt% UO_2, 20wt% ZrO_2
- Melt temperature: 3052 K
- Melt jet diameter: 50 mm
- Melt fall height: 0.89 m
- System pressure: 0.5 MPa
- Cover gas: Steam
- Water pool size: depth 1.44 m, diameter 0.71 m
- Water temperature: 424 K (subcool 1 K)
- Results: Melt was partially broken-up, partially agglomerated. Detail was not described.

References

1) D. Magallon et al., Implication of FARO and KROTOS experiments for FCI issues, OECD Workshop on ex-vessel debris coolability, Germany, 1999.

II.1.b

The system pressure is near the range of PWR/BWR ex-vessel FCI conditions. The longest melt pour period in FARO series is favorable to establish steady state jet breakup situation expected in the reactor condition. Water pool at saturation temperature is in the rage of PWR condition specified above. Melt composition is close to the PWR condition although lacking Zr metal and steel components.

II.1.c, d, e : nothing to comment.

8.3. II.2.a FARO L-31, JRC-Ispra, EU

Corium jet breakup and mixing in a subcooled water pool at 0.2MPa.

- Melt mass: 92 kg
- Melt composition: 80wt% UO_2, 20wt% ZrO_2
- Melt temperature: 2990 K
- Melt jet diameter: 50 mm
- Melt fall height: 0.77 m
- System pressure: 0.2 MPa
- Cover gas: Argon
- Water pool size: depth 1.45 m, diameter 0.71 m
- Water temperature: 291 K (subcool 104 K)
- Results: Melt was totally broken-up.

References

1) D. Magallon et al., Implication of FARO and KROTOS experiments for FCI issues, OECD Workshop on ex-vessel debris coolability, Germany, 1999.

2) D. Magallon and I. Huhtiniemi, Corium melt quenching tests at low pressure and subcooled water in FARO, Nuclear Engineering and Design, 204, 369--376, 2001.

II.2.b

The system pressure is near the range of PWR/BWR ex-vessel FCI conditions. Water pool with large subcool corresponds to the BWR condition specified above. Melt composition is close to the PWR condition although lacking Zr metal and steel components.

II.2.c, d, e : nothing to comment.

III. Relevant Explosion Experiments

8.4. III.1.a FARO L-33, JRC-Ispra, EU

Externally triggered propagating event with relatively large amount of corium melt in a large subcooled water pool.

- Melt mass: 100 kg (40 kg under water at the time of triggering)
- Melt composition: 80wt% UO_2, 20wt% ZrO_2
- Melt temperature: 3070 K
- Melt jet diameter: 50 mm
- Melt fall height: 0.77 m
- System pressure: 0.4 MPa
- Cover gas: Argon
- Water pool size: depth 1.60 m, diameter 0.71 m
- Water temperature: 293 K (subcool 124 K)
- Results: Propagating event was observed. Detail not available.

References

1) D. Magallon et al., Implication of FARO and KROTOS experiments for FCI issues, OECD Workshop on ex-vessel debris coolability, Germany, 1999.

III.1.b

This is the only experiment in which an explosive event was triggered with large amount of corium melt in a large subcooled water pool. The system pressure is near the range of PWR/BWR ex-vessel FCI conditions. Water pool with large subcool corresponds to the BWR condition specified above. Melt composition is close to the PWR condition although lacking Zr metal and steel components.

III.1.c, d, e : nothing to comment.

8.5. III.2.a KROTOS K-58, JRC-Ispra, EU

Externally triggered propagating event with corium melt in a subcooled water pool.

- Melt mass: 4.5 kg
- Melt composition: 80wt% UO_2, 20wt% ZrO_2
- Melt temperature: 3077 K
- Melt jet diameter: 30 mm
- System pressure: 0.37 MPa
- Cover gas: Helium
- Water pool size: depth 0.92 m, diameter 0.20 m
- Water temperature: 289 K (subcool 125 K)
- Results: Propagating event was observed.

References

1) D. Magallon et al., Implication of FARO and KROTOS experiments for FCI issues, OECD Workshop on ex-vessel debris coolability, Germany, 1999.

2) I. Huhtiniemi and D. Magallon, Insight into steam explosion with corium melts in KROTOS, Nuclear Engineering and Design, 204, 391--400, 2001.

III.2.b

The system pressure is near the range of PWR/BWR ex-vessel FCI conditions. Water pool with large subcool corresponds to the BWR condition specified above. Melt composition is close to the PWR condition although lacking Zr metal and steel components.

III.2.c, d, e : nothing to comment.

III.3.a TROI UO_2/ZrO_2 experiment No.13, KAERI, Korea

Spontaneous steam explosion with corium melt in a subcooled water pool.

⑩Melt mass: 7.7 kg
⑩Melt composition: 70wt% UO_2, 30wt% ZrO_2
⑩Melt temperature: 3000 K (uncertainty due to gray body assumption?)
⑩Melt jet diameter: 20 mm
⑩System pressure: 0.108 MPa
⑩Cover gas: Air
⑩Water pool size: depth 0.67 m, diameter 0.6 m
⑩Water temperature: 292 K (subcool 83 K)
⑩Results: Spontaneous steam explosion was observed.

References
1) J.H. Song et al., Fuel Coolant Interaction Experiments in TROI Using UO_2/ZrO_2 Mixture, Draft paper distributed to SERENA participants, Jan 2002.

III.3.b

This is the recent experiment in which a spontaneous explosion was observed maybe because of a large initial superheat of melt. Although the high superheat condition is different from the reactor cases, it is worth examining whether the explosivity observed in the experiment can be simulated with current models. The system pressure is lower than the range of PWR/BWR ex-vessel FCI conditions. Water pool with large subcool corresponds to the BWR condition specified above. Melt composition is close to the PWR condition although lacking Zr metal and steel components.

III.3.c, d, e : nothing to comment.

OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in Npp's

KAERI/KMU Contribution

by
Jinho Song and Kwanghyun Bang

Summary

With our practical interest to come to a reasonable conclusion on the risk of Fuel Coolant Interaction (FCI) in the operating Nuclear Power Plants and Advanced Light Water reactors (ALWRs) under development in Korea, a brief status quo about the Korean nuclear plants is described in section 0.

In section 1, relevant conditions for the energetic FCI for Korean Standard Nuclear Power Plants (KSNPs) and APR-1400 (Advanced Pressurized water Reactor-1400 Mwe) are identified in the aspect of severe accident management.

In section 2, three premixing cases; QUEOS-32, FARO L-14 and L-31, are proposed for the premixing calculations. QUEOS-32 using hot solid spheres is proposed because analysis of this experiment can be focused solely on the physics of pre-mixing without being too much disturbed by the jet break up. Also, two integral tests in one test facility with distinct experimental conditions are selected to check the consistency of code predictions.

In section 3, three experiments; KROTOS-37, KROTOS-44, and TROI-13 are proposed for the explosion analyses. Though KROTOS-44 is a very good case for an explosion calculation, one major shortcoming is that the experiment was perfomed using Alumina, so it might not be directly relevant to a real reactor situation. KROTOS-37 is a typical explosion case using prototypic melt material. But as it did not lead to an energetic explosion, it may not be the proper case for exercising explosion calculation. TROI-13 is proposed as a highly preferred experiment since it is the only experiment yet performed with prototypic material having a spontaneous steam explosion. The experiment has well defined initial and boundary conditions and the data are well documented with appropriate QA procedure.

0. AVANT-PROPOS

0.1 Status of Korean nuclear power plants:

There are 16 nuclear power plants (12 PWRs and 4 PHWRs) in commercial operation, as shown in Table1. Ulchin Units 3 & 4 are envisioned as the lead units in the series of 1,000 MWe class KSNPs to be built, including two reactors in North Korea. According to the long-term plan of Korean nuclear power development , the 1,000MWe class KSNP design will be continuously upgraded to enhance safety and economic efficiency. Also, development of the 1,400MWe APR design will continue.

By the long-term electric power supply plan, eight more units consisting of four KSNPs and four APR 1400s will be built by 2015, and commercial operation of the first APR1400 unit is scheduled for 2010. In 2015, the installed nuclear capacity will be increased to 27,316MW, comprised of 28 units, sharing about 33% of the total installed capacity.

Table 1. Korean Nuclear Power Plants

	8.6. Kori	Yonggwang	**8.7. Ulchin**	**8.8. Wolsong**
Units	4	4+2(under commissioning test)	4+2(under construction)	4
Reactor Type	PWR	PWR	PWR	PHWR
Capacity (MW)	3137	3900	3900	2779
Vender	Westinghouse	Westinghouse (1,2) ABB-CE (3,4) KOPEC/Doojung(5,6)	Framatome (1,2) KAERI/Doojung (3,4) KOPEC/Doojung(5,6)	AECL/KAERI

0.2 Risk of Steam Explosion in the Aspect of Severe Accident Management

The risk of steam explosion is closely related to the development of severe accident management strategy for the operating reactors like KSNPs and also for the APR1400 which is now under development. By the government policy on severe accident of NPP, the Korean utility should provide a severe accident management program for every NPPs. SAM programs for KSNPs and APR1400 are actually under licencing review by Korean regulatory body.

For these reactors, the strategy of in-vessel-retention(IVR) of molten corium through external cooling of the reactor vessel is adopted to mitigate severe accident progress. According to the proposed SAM, in case a core melting is susceptible, the reactor cavity will be first filled by Cavity Flooding System(CFS) to the height of 1.524m from the floor. For SBO or other high pressure accidents the molten fuel debris will be cooled in this condition. For other low pressure accidents where the IVR is feasible, water will be filled to the level of hot leg to cool the RPV externally.

The see the feasibility of this IVR strategy, we also need to evaluate the adverse effects of FCI when the in-vessel-retention fails. Though the IVR is evaluated to be feasible for the small power reactors like Loviisa or AP-600, the margin of IVR for the high power reactors is believed to be rather small, if not "not-feasible".

As the reactor cavity is flooded with cold water, the ex-vessel steam explosion is possible when there is a breach of reactor vessel pressure boundary, such as a failure of in core instrumentation nozzles.

Another scenario for the potential steam explosion is that one which will occur when the water is injected on top of the molten core while the reactor coolant system is fully depressurized for an ex-vessel cooling. It might cause an in-vessel steam explosion at low pressure, which is quite similar to the ex-vessel steam explosion case. However, the melt water contact mode is different, as the water is injected on top of the molten core, where the metallic layer might float on top of the oxide pool. The structural loads to either the reactor pressure vessel or the reactor cavity due to energetic steam explosion needs to be properly evaluated.

I. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

Figure 1 and Figure 2 show the cavity configurations of the APR1400 and KSNP respectively. The relevant geometric and accident conditions are summarised in the following tables.

Table 2. Geometry data of KSNP and APR-1400

Geometry	KSNP	APR1400
Mass	UO2 : 86 ton , Zr : 24 ton	UO2 : 119.98 ton, Zr : 33.58 ton
Cavity floor area	67.6 m^2	80.445 m^2
Cavity volume	354.25 m^3, from 55 ft to 80 ft (BH at ~83.9′)	756 m^3 (available volume for IVR)
Distance (m)	floor to LH ~ 6.85 m, floor to BH ~ 8.8m	floor to LH ~ 6.85m floor to BH ~ 9.2m
ID of lower RV	~ 4.2 m	~ 4.7 m
Lower plenum volume	27.2 m^2	
No. of ICI nozzles	45	61
Material, OD ICI nozzle	Inconel 690, 7.62 cm	Inconel 690, 7.62 cm

The conditions at the time of accident was calculated by the widely used severe accident analysis code MELCOR 1.8.5. The representative scenario assumed is LBLOCA with SITs and no HPSI. In fact the values are averaged one for the scenarios like medium LOCA with SIT and no HPSI or small LOCA with no HPSI.

Table 3. Accident Conditions for KSNP and APR-1400

	KSNP	APR1400
Accident Conditions		
Containment Pressure	~0.26MPa	~0.26 MPa
Met temperature	~2800K	~ 2800K
Molten core mass	Oxide ~66 ton, Metal ~35 ton	Oxide ~111 ton, metal ~ 47 ton
Melt composition	UO_2 ~60 ton, ZrO_2 ~6 ton	UO_2 ~102.4 ton, ZrO_2 ~8.6 ton
Pool temperature	~ 320K	~ 320K

I.2 Important Parameters relevant to reactor condition

Melt composition: Prototypic melt composition is very important. As the effect of material property on the steam explosion energy is the least understood part of the risk of steam explosion. The importance of this effect is H.

Met mass: The effect of scaling is a still unknown area. While the prototypic reactor condition deals with tons of molten reactor materials, the scale of existing steam explosion experiments is between 1 – 150 kg. The condition for the ex-vessel steam explosion could be simplified as a melt jet of 7 cm in 1 m pool to simulate a melt jet coming from the ICI nozzle. It requires about 30 kg of corium. The effect of multiple melt jet in contact with water might be handled in an evaluative manner. The effect of scale for the in-vessel steam explosion is very complicated and it needs to be revisited. The importance of this effect is H.

Pool Geometry: The ratio of the cross sectional area of melt jet to water pool and the ratio of water to melt are the major parameters influencing the premixing and explosion behaviour, as they provide water volume for the melt water interaction and flow area for the venting of steam generated from the leading portion of the melt jet. So, they need to be preserved in the experiments. Certainly, there is a multi-dimensional effect in the prototypic condition. The importance of this effect is H.

Water temperature: The increase in water temperature tends to increase the magnitude of steam explosion. So, we need to have some experimental data for computational model to determine this effect. The importance of this effect is M. The triggered experiment at room temperature might represent the upper limit.

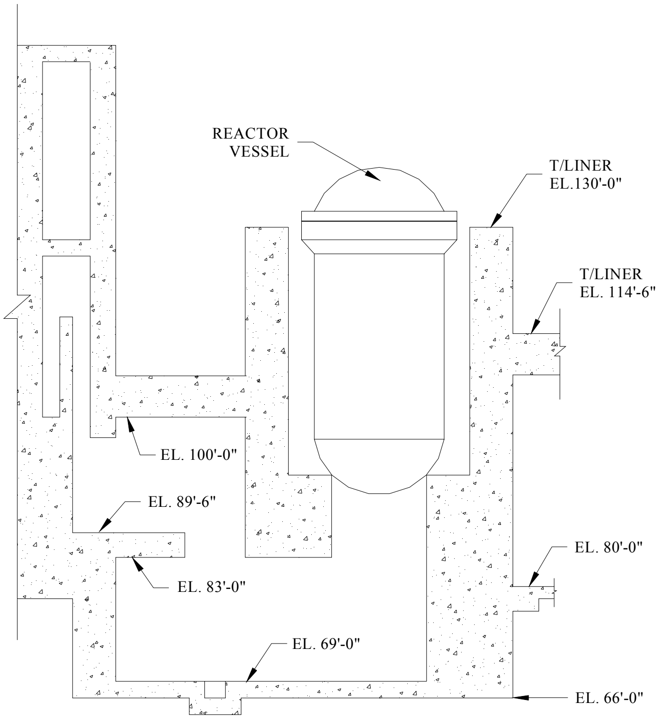
Environment Pressure: High system pressure tends to suppress the mechanism which causes steam explosion. As the environmental pressure for the ex-vessel steam explosion is between 0.2– 0.5 MPa, we need to have an experimental data at this pressure condition. Also, we should have an analytical model to evaluate this effect. The importance of this effect is H. The experimental pressure should be at 0.2– 0.5 Mpa

Melt velocity: Distance for the jet to fall and the system pressure determines the melt jet velocity. Melt jet velocity will affect the premixing behaviour and melt jet fragmentation. The importance of this effect is M. Free fall height should be similar to the prototypic condition 1-8 m.

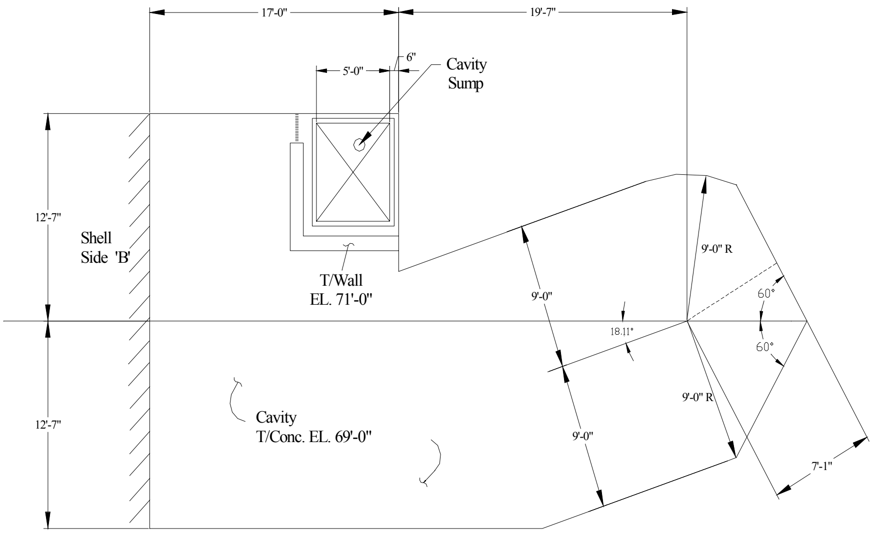
Melt temperature: There is an effect of melt superheat. We need some experimental data or analytical model to evaluate this effect. However, the importance of this effect is L. Superheat of 100-200 K might be enough.

Table 4. Summary of relevant conditions

	Rank	Relevant condition
Melt composition	H	Prototypic composition
Melt mass	H	Nozzle at 7 cm, > 30 kg
Pool geometry	H	Multi-dimensional Enough water to melt mass ratio
Water temperature	M	Triggered experiment would represent upper limit
Environmental pressure	H	0.2 – 0.5 Mpa
Melt velocity	M	Free fall height 1 – 8 m
Melt temperature	M	Enough super heat 100-200 K



SECTION VIEW



PLANE VIEW

FIGURE-1 : APR1400 Cavity Configuration

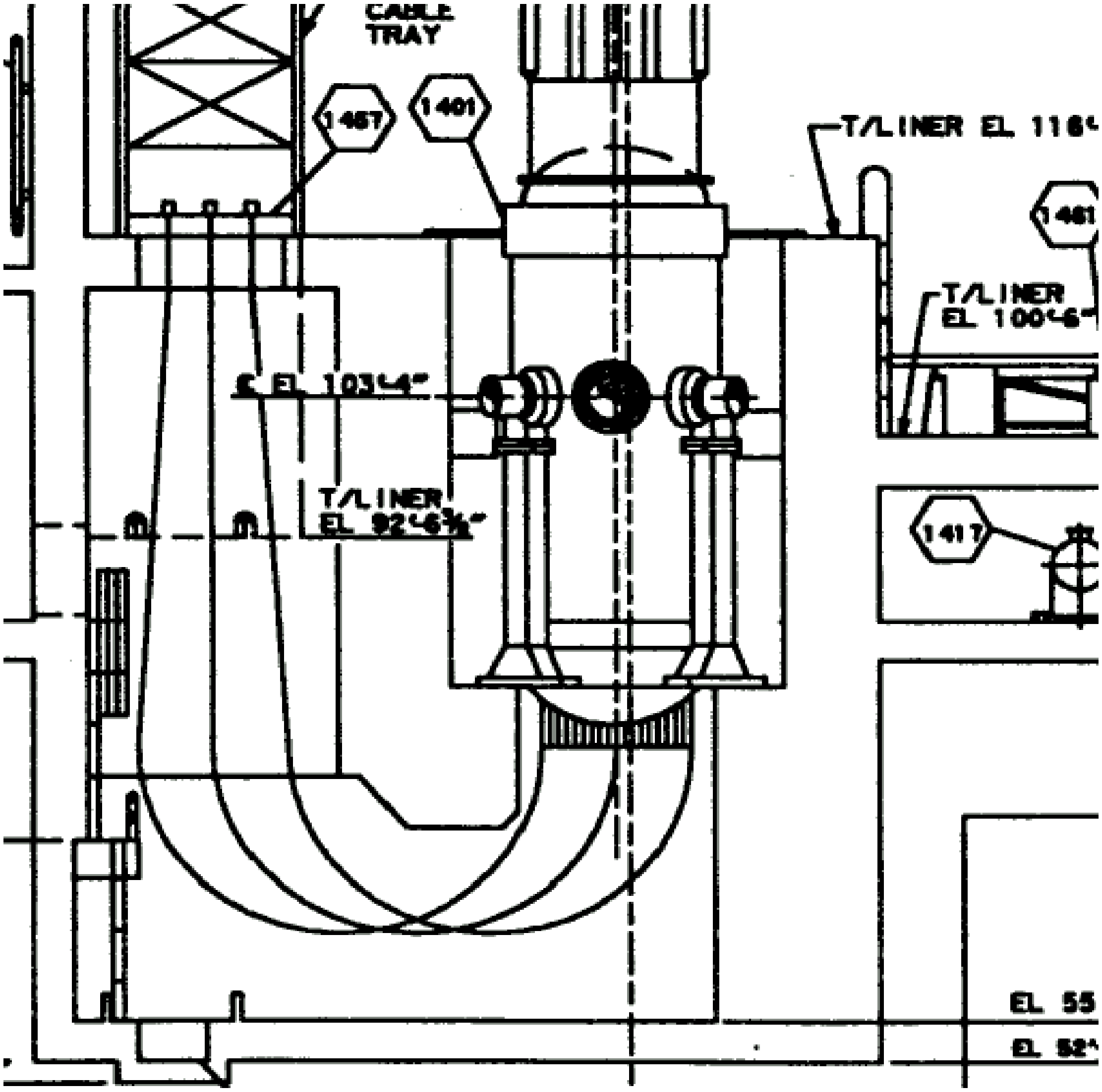


FIGURE-2 : KSNP Cavity Configuration

II. RELEVANT PREMIXING EXPERIMENTS

The premixing phase of FCIs is a complicated physical phenomenon that encompasses melt jet and drop breakup, multiphase heat and momentum transfer and phase change, radiation heat transfer. Due to this multifield nature of the phenomena, integral experiments using molten material alone may not be sufficient for code calculation for validation purpose. To separate the complicated physics of melt breakup and multiphase heat and momentum transport, the calculation of a premixing experiment using hot solid spheres is also preferable. Besides, two tests in one test facility with distinctively different experimental conditions are desirable to check the consistency in code predictions. With these backgrounds, three tests are recommended for premixing calculation: QUEOS-32, FARO L-14 and L-31.

II.1 QUEOS-32

II.1.a Description of the experiment:

About 36,000 solid balls of zirconium oxide with 5 mm diameter were poured into a transparent square tank. The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 9.

II.1.b Relevance to reactor conditions: L

This test was performed using hot solid balls and the initial temperature of the balls was about 1800 K, which is 1,000 K lower than the typical melt in reactor cases. However, it will be a useful data because one can rule out the uncertainty associated with melt breakup in premixing calculation.

II.1.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.1.d Quality of data: H

Visualization of the mixture volume is provided and dynamic pressure and steaming rate were measured.

II.1.e Unresolved discrepancies with previous calculations

The video frames show clear view of mixture volume and it is seen that there is a region of liquid water alone just upper part of mixture volume. But in code calculation such region is not normally found, but mostly steam-water two-phase volumes. It depends on steam-water heat transfer and condensation model, particularly in very low water subcooling (a few degrees).

II.2 FARO L-14

II.2.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 2 and 3.

II.2.b Relevance to reactor conditions: M

This test was performed using prototypic corium at high temperature. But ambient pressure was high (51 bars) so it may be relevant to in-vessel FCIs, but might not be relevant to reactor conditions if the primary system pressure is fully depressurised either by an initiating event of

LOCA or actuation of SDS to avoid DCH.

II.2.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.2.d Quality of data: H

The data have been well measured and documented.

II.2.e Unresolved discrepancies with previous calculations

This test had been extensively used in ISP-39 work and the predictions of various codes spread over unacceptable band.

II.3 FARO L-31

II.3.a Description of the experiment:

The major differences in the experimental conditions between L-14 and L-31 are melt jet diameter (100:50), initial pressure (51:2), water temperature (537:291). The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 1.

II.3.b Relevance to reactor conditions: H

This test was performed using prototypic corium at high temperature. The ambient pressure was low (2.1 bars) so it is highly relevant to reactor conditions.

II.3.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.3.d Quality of data: H

The data have been well measured and documented.

II.3.e Unresolved discrepancies with previous calculations

No calculation.

II.4 Selection Criteria and Ranking for Pre-mixing case

Based on the discussions above, the conclusion of the ranking is summarized in the table below.

Table 5. Proposed experiments and results of ranking for pre-mixing case

	QUEOS-32	L-14	L-31
Relevance to reactor conditions	L	M	H
Quality of data	H	H	H
Level of characterization of initial conditions	H	H	H
Used Material	ZrO2	UO2/ZrO2 (8:2)	UO2/ZrO2 (8:2)
Unresolved discrepancies with previous calculations	Phase change	ISP-39	
Comments	Solid balls		

III. RELEVANT EXPLOSION EXPERIMENTS

As discussed in section 1, the highly ranked parameters for the prototypic condition are the melt composition, melt mass, pool geometry and environmental pressure. TROI-13 matches all these criteria best. Though KROTOS-44 is a very nice set of test for explosion calculation, it might not be relevant to the reactor conditions, for Alumina was used instead of prototypic material. KROTOS-37 is a typical explosion experiment using prototypic melt. However, it did not lead to an energetic explosion. The initial and boundary conditions for those three experiments are listed in Table 7. Table 6 lists the results of explosion ranking for the code comparison.

III.1 KROTOS: K-37

III.1.a Description of the experiment:

KROTOS-44 is a typical explosion experiment using a prototypic melt of UO_2/ZrO_2 mixture at 80:20. The details of the experimental conditions, summary of results, precise references can be found in Table 7, References 6, and Reference 7

III.1.b Relevance to reactor conditions: M

The typical contact mode of ex-vessel steam explosion is at low-pressure, sub-cooled water, the diameter of melt jet at about 7 cm, water depth at about 1- 8 m, free fall height at about 1-8 m.

Two conditions are rather far from typical ex-vessel FCI mode. The first one is the melt geometry. To simulate the prototypic condition, we should simulate a melt jet of 7 cm in 1 m pool, which requires about 31 kg of corium. So, melt jet diameter and amount of melt is rather different from typical ex-vessel condition. The second one is the pool geometry. The ratio of the cross sectional area is one of the major parameters influencing the premixing and explosion behaviour, as it provides water volume for the melt water interaction and flow area for the venting of steam generated from the leading portion of the melt jet. So, it needs to be preserved in the experiments.

The test section of the KROTOS is a kind of one-dimensional shape, where a cylindrical test section with a 200mm inner diameter is used. The initial jet diameter in the KROTOS experiment is about 30 mm, which leads to a water to fuel ratio of 30 in terms of the cross sectional area. The typical ex-vessel FCI mode provides much bigger water to melt cross-sectional area ratio. The ranking is M.

III.1.c Level of characterisation of initial and boundary conditions: L

Though it is not clear whether melt jet is well maintained by the melt delivery mechanism used in the KROTOS, initial and boundary conditions are well defined. However, K-37 did not result in energetic reaction, so it is not suitable for the code calculation. The ranking is L.

III.1.d Quality of data: H

The quality of JRC data is excellent. The ranking is H.

III.1.e Unresolved discrepancies with previous calculations: Yes

There were discussions and code comparisons [7] on the role of hydrogen generation for the non-explosive nature of the tests. It is not clear whether hydrogen generation was measured for the K-37 test.

III.2 KROTOS: K-44

III.2.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7, References 6, and Reference 7

III.2.b Relevance to reactor conditions: L

It is Alumina test and it has similar test conditions as those of K-37. As the effect of material is the least understood part of the steam explosion model, it might be not relevant to the reactor condition. The ranking is L.

III.2.c Level of characterisation of initial and boundary conditions: L

As it has similar test conditions as those of K-37, the ranking is L.

III.2.d Quality of data: H

The quality of JRC data is excellent. The ranking is H.

III.2.e Unresolved discrepancies with previous calculations: Yes.

The code predictions and results of code calculation agree reasonably. However since the material used was Alumina, it cannot address the effect of material property.

III.3 TROI-13

III.3.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7, Reference 4, and Reference 5

III.3.b Relevance to reactor conditions: H

The typical contact mode of ex-vessel steam explosion is at low-pressure, sub-cooled water, the diameter of melt jet at about 7 cm, water depth at about 1- 8 m, free fall height at about 1-8 m.

To simulate the prototypic condition, we should simulate a melt jet of 7 cm in 1 m pool, which requires about 31 kg of corium. As the amount of melt is about 7 kg and the melt jet diameter is 2 cm. So, it is rather far from typical ex-vessel FCI mode. As the initial melt jet diameter of this test is about the same as that of KROTOS, TROI provides much bigger water to melt cross-sectional area ratio. It is better in terms of preserving ratio of cross sectional area of melt and water. The ranking is H

III.3.c Level of characterisation of initial and boundary conditions: M

TROI-13 resulted in a spontaneous steam explosion. The dynamic pressure, impulse, pressure and temperature responses of the test section and containment chamber were measured. The initial and boundary conditions are well defined. As the response of the system is rather multi-dimensional, there might be some difficulties in performing code calculations and in comparing the results with experimental results. The one-dimensional pressure propagation cannot be simulated. The ranking is M.

III.3.d Quality of data: H

The quality of KAERI data is reasonable. The ranking is H.

III.3.e Unresolved discrepancies with previous calculations: Yes

As there was no code calculations for the TROI-13, there might be some discrepancies.

III.4 Selection Criteria and Ranking for Explosion case

Based on the discussions above, the conclusion of the ranking is summarized in the following table

Table 6. Proposed experiments and results of ranking for explosion case

	K-37	K-44	TROI-13
Relevance to reactor conditions	M	L	H
Quality of data	H	H	H
Level of characterization of initial conditions	L	M	M
Used Material	H	L	H
Unresolved discrepancies with previous calculations	Hydrogen generation	Material effect	Probably
Comments			Better data expected in near future

Table 7. Initial and Boundary conditions for the major SE experiments using Corium

	QUEOS-32	L-31	L-14	TROI-13	K-37	K-44
Melt Mass (kg)	14 (5 mm)	92	125	7.7	3.2	1.5
Composition (UO_2/ZrO_2)	ZrO2	80:20	80:20	70:30	79:21	Alumina
Melt Temperature (K)	1818	2990	3100	~3300 K	~3018	2625
Melt Release Diameter (mm)	100	50	Nozzle 100	20	Initial Jet 30	
Test Section Diameter (m)	0.7x0.7	0.71	0.71	0.6	0.2	0.2
Initial Pressure (MPa)	0.1	0.21	5.1	0.1	0.1	0.21
Atmosphere	Air	Ar	77% steam, 23% Ar	Air	He	NR
Free Board Volume (m^3)	0.68	3.54	1.26	8.03		NR
Melt Fall Height (m)	1.3	0.74	1.04	3.9	0.44	0.44
Water Depth (m)	1.0	1.45	2.05	0.67	1.105	1.3
Water Temperature (K)	372	291	537	292	294	295
Water Mass (K)	490	492	623	189	34.5	34.8
H2 Generation	NR	NR	NR	Negligible	NR	NR
Debris	NA	< 1mm, ~5%	< 1mm, ~5%	< 1mm, ~40%	1.4 mm mass mean	0.1 mm mass mean
Steam Explosion	No	No	No	Yes	No	Yes
Typical Data	Video Steam rate P	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T
Dynamic Pressure	Yes	No	No	Measured	No	Measured
Trigger	No	No	No	No	Yes	Yes
Reference	9	1	2,3	4,5	6,7	7,8

References

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OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in Npp's

KINS Contribution

by
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Summary

With our practical interest to come to a reasonable conclusion on the risk of FCI in the operating and also under development Korean NPPs, brief status quo about the Korean nuclear plants is described in section 0.

In section 1, relevant conditions for the energetic FCI for Korean Standard Nuclear Power Plants (KSNPs) and APR-1400 (Advanced Pressurized water Reactor-1400 Mwe) are identified in the aspect of severe accident management. In section 2, three premixing cases; QUEOS-32, FARO L-14 and L-31, are proposed for the premixing calculations. QUEOS-32 using hot solid spheres is proposed because analysis of this experiment can be focused solely on the physics of pre-mixing without being too much disturbed by the other complicated phenomena.. Also, two integral tests in one test facility with distinct experimental conditions are selected to check the consistency of code predictions.

In section 3, three experiments; KROTOS-37, KROTOS-44, and TROI-13 are proposed for the explosion analyses. Though KROTOS-44 is a very good case for an explosion calculation, one major shortcoming is that the experiment was perfomed using Alumina, so it might not be directly relevant to a real reactor situation. KROTOS-37 is a typical explosion case using prototypic melt material. But as it did not lead to an energetic explosion , there are concerns that we might lose the real explosion physics even though we analyze the case. TROI-13 is proposed as a highly preferred experiment since it is the only experiment yet performed with prototypic material having a spontanous steam explosion. The experiment has well defined initial and boundary conditions and the quality of data is assured.

0. AVANT-PROPOS

0.1 Status of Korean nuclear power plants:

There are 16 nuclear power plants (12 PWRs and 4 PHWRs) in commercial operation, as shown in Table1. Ulchin Units 3 & 4 are envisioned as the lead units in the series of 1,000 MWe class KSNPs to be built, including two reactors in North Korea. According to the long-term plan of Korean nuclear power development , the 1,000MWe class KSNP design will be continuously upgraded to enhance safety and economic efficiency. Also, development of the 1,400MWe APR design will continue.

By the long-term electric power supply plan, eight more units consisting of four KSNPs and four APR 1400s will be built by 2015, and commercial operation of the first APR1400 unit is scheduled for 2010. In 2015, the installed nuclear capacity will be increased to 27,316MW, comprised of 28 units, sharing about 33% of the total installed capacity.

Table 1. Korean Nuclear Power Plants

	8.9. Kori	Yonggwang	**8.10. Ulchin**	**8.11. Wolsong**
Units	4	4+2(under commissioning test)	4+2(under construction)	4
Reactor Type	PWR	PWR	PWR	PHWR
Capacity (MW)	3137	3900	3900	2779
Vender	Westinghouse	Westinghouse (1,2) ABB-CE (3,4) KOPEC/Doojung(5,6)	Framatome (1,2) KAERI/Doojung (3,4) KOPEC/Doojung(5,6)	AECL/KAERI

0.2 Risk of Steam Explosion in the Aspect of Severe Accident Management

The risk of steam explosion is closely related to the development of severe accident management strategy for the operating reactors like KSNPs and also for the APR1400 which is now under development. By the government policy on severe accident of NPP, the Korean utility should provide a severe accident management program for every NPPs. SAM programs for KSNPs and APR1400 are actually under licencing review by Korean regulatory body.

For these reactors, the strategy of in-vessel-retention(IVR) of molten corium through external cooling of the reactor vessel is adopted to mitigate severe accident progress. According to the proposed SAM, in case a core melting is susceptible, the reactor cavity will be first filled by Cavity Flooding System(CFS) to the height of 1.524m from the floor. For SBO or other high pressure accidents the molten fuel debris will be cooled in this condition. For other low pressure accidents where the IVR is feasible, water will be filled to the level of hot leg to cool the RPV externally.

The see the feasibility of this IVR strategy, we also need to evaluate the adverse effects of FCI when the in-vessel-retention fails. Though the IVR is evaluated to be feasible for the small power reactors like Loviisa or AP-600, the margin of IVR for the high power reactors is believed to be rather small, if not “not-feasible”.

As the reactor cavity is flooded with cold water, the ex-vessel steam explosion is possible when there is a breach of reactor vessel pressure boundary, such as a failure of in core instrumentation nozzles.

Another scenario for the potential steam explosion is that one which will occur when the water is injected on top of the molten core while the reactor coolant system is fully depressurized for an ex-vessel cooling. It might cause an in-vessel steam explosion at low pressure, which is quite similar to the ex-vessel steam explosion case. However, the melt water contact mode is different, as the water is injected on top of the molten core, where the metallic layer might float on top of the oxide pool. The structural loads to either the reactor pressure vessel or the reactor cavity due to energetic steam explosion needs to be properly evaluated.

I. RELEVANT CONDITIONS FOR ENERGETIC FCI IN NPP'S

Figure 1 and Figure 2 show the cavity configurations of the APR1400 and KSNP respectively. The relevant geometric and accident conditions are summarised in the following tables.

Table 2. Geometry data of KSNP and APR-1400

Geometry	KSNP	APR1400
Mass	UO2 : 86 ton , Zr : 24 ton	UO2 : 119.98 ton, Zr : 33.58 ton
Cavity floor area	67.6 m^2	80.445 m^2
Cavity volume	354.25 m^3, from 55 ft to 80 ft (BH at ~83.9′)	756 m^3 (available volume for IVR)
Distance (m)	floor to LH ~ 6.85 m, floor to BH ~ 8.8m	floor to LH ~ 6.85m floor to BH ~ 9.2m
ID of lower RV	~ 4.2 m	~ 4.7 m
Lower plenum volume	27.2 m^2	
No. of ICI nozzles	45	61
Material, OD ICI nozzle	Inconel 690, 7.62 cm	Inconel 690, 7.62 cm

The conditions at the time of accident was calculated by the widely used severe accident analysis code MELCOR 1.8.5. The representative scenario assumed is LBLOCA with SITs and no HPSI. In fact the values are averaged one for the scenarios like medium LOCA with SIT and no HPSI or small LOCA with no HPSI.

Table 3. Accident Conditions for KSNP and APR-1400

	KSNP	APR1400
Accident Conditions		
Containment Pressure	~0.26MPa	~0.26 MPa
Met temperature	~2800K	~ 2800K
Molten core mass	Oxide ~66 ton, Metal ~35 ton	Oxide ~111 ton, metal ~ 47 ton
Melt composition	UO_2 ~60 ton, ZrO_2 ~6 ton	UO_2 ~102.4 ton, ZrO_2 ~8.6 ton
Pool temperature	~ 320K	~ 320K

I.2 Important Parameters relevant to reactor condition

Melt composition: Prototypic melt composition is very important. As the effect of material property on the steam explosion energy is the least understood part of the risk of steam explosion. The importance of this effect is H.

Met mass: The effect of scaling is a still unknown area. While the prototypic reactor condition deals with tons of molten reactor materials, the scale of existing steam explosion experiments is between 1 – 150 kg. The condition for the ex-vessel steam explosion could be simplified as a melt jet of 7 cm in 1 m pool to simulate a melt jet coming from the ICI nozzle. It requires about 30 kg of corium. The effect of multiple melt jet in contact with water might be handled in an evaluative manner. The effect of scale for the in-vessel steam explosion is very complicated and it needs to be revisited. The importance of this effect is H.

Pool Geometry: The ratio of the cross sectional area of melt jet to water pool and the ratio of water to melt are the major parameters influencing the premixing and explosion behaviour, as they provide water volume for the melt water interaction and flow area for the venting of steam generated from the leading portion of the melt jet. So, they need to be preserved in the experiments. Certainly, there is a multi-dimensional effect in the prototypic condition. The importance of this effect is H.

Water temperature: The increase in water temperature tends to increase the magnitude of steam explosion. So, we need to have some experimental data for computational model to determine this effect. The importance of this effect is M. The triggered experiment at room temperature might represent the upper limit.

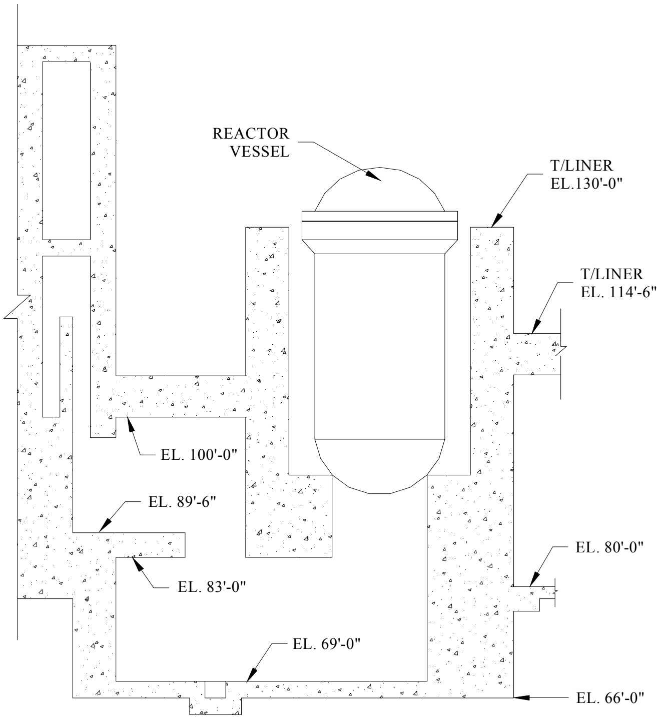
Environment Pressure: High system pressure tends to suppress the mechanism which causes steam explosion. As the environmental pressure for the ex-vessel steam explosion is between 0.2– 0.5 MPa, we need to have an experimental data at this pressure condition. Also, we should have an analytical model to evaluate this effect. The importance of this effect is H. The experimental pressure should be at 0.2– 0.5 Mpa

Melt velocity: Distance for the jet to fall and the system pressure determines the melt jet velocity. Melt jet velocity will affect the premixing behaviour and melt jet fragmentation. The importance of this effect is M. Free fall height should be similar to the prototypic condition 1-8 m.

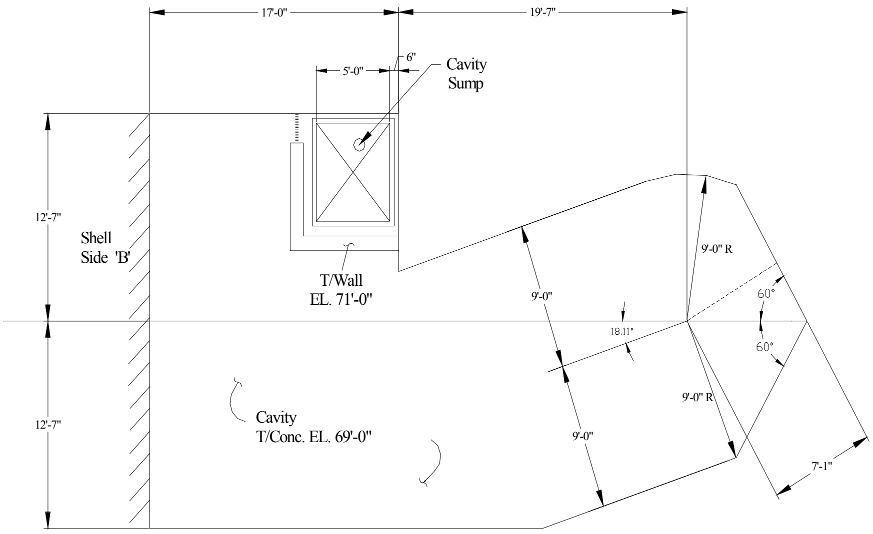
Melt temperature: There is an effect of melt superheat. We need some experimental data or analytical model to evaluate this effect. However, the importance of this effect is L. Superheat of 100-200 K might be enough.

Table 4. Summary of relevant conditions

	Rank	Relevant condition
Melt composition	H	Prototypic composition
Melt mass	H	Nozzle at 7 cm, > 30 kg
Pool geometry	H	Multi-dimensional Enough water to melt mass ratio
Water temperature	M	Triggered experiment would represent upper limit
Environmental pressure	H	0.2 – 0.5 Mpa
Melt velocity	M	Free fall height 1 – 8 m
Melt temperature	M	Enough super heat 100-200 K



SECTION VIEW



PLANE VIEW

FIGURE-1 : APR1400 Cavity Configuration

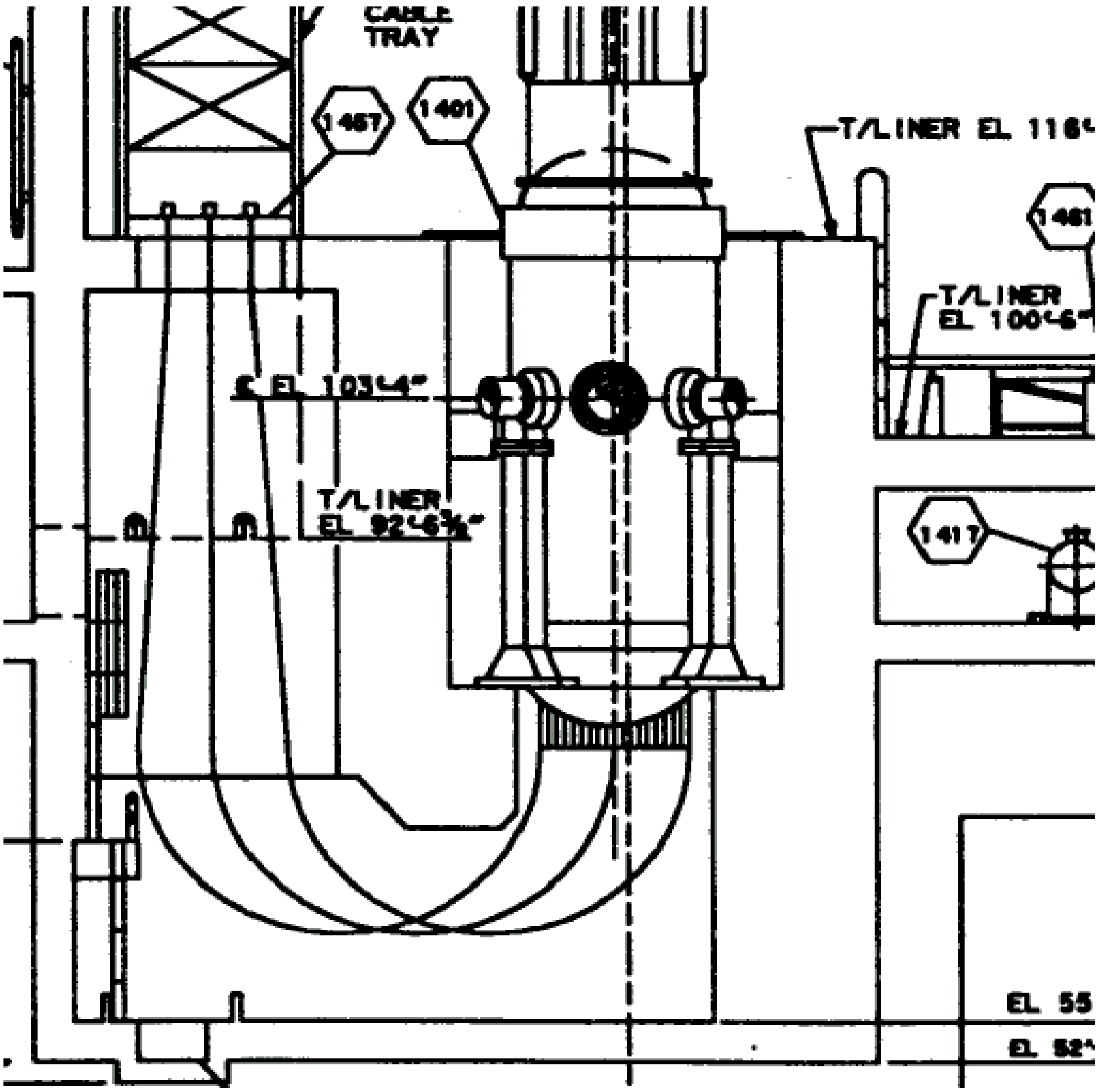


FIGURE-2 : KSNP Cavity Configuration

II. RELEVANT PREMIXING EXPERIMENTS

The premixing phase of FCIs is a complicated physical phenomenon that encompasses melt jet and drop breakup, multiphase heat and momentum transfer and phase change, radiation heat transfer. Due to this multifield nature of the phenomena, integral experiments using molten material alone may not be sufficient for code calculation for validation purpose. To separate the complicated physics of melt breakup and multiphase heat and momentum transport, the calculation of a premixing experiment using hot solid spheres is also preferable. Besides, two tests in one test facility with distinctively different experimental conditions are desirable to check the consistency in code predictions. With these backgrounds, three tests are recommended for premixing calculation: QUEOS-32, FARO L-14 and L-31.

II.1 QUEOS-32

II.1.a Description of the experiment:

About 36,000 solid balls of zirconium oxide with 5 mm diameter were poured into a transparent square tank. The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 9.

II.1.b Relevance to reactor conditions: L

This test was performed using hot solid balls and the initial temperature of the balls was about 1800 K, which is 1,000 K lower than the typical melt in reactor cases. However, it will be a useful data because one can rule out the uncertainty associated with melt breakup in premixing calculation.

II.1.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.1.d Quality of data: H

Visualization of the mixture volume is provided and dynamic pressure and steaming rate were measured.

II.1.e Unresolved discrepancies with previous calculations

The video frames show clear view of mixture volume and it is seen that there is a region of liquid water alone just upper part of mixture volume. But in code calculation such region is not normally found, but mostly steam-water two-phase volumes. It depends on steam-water heat transfer and condensation model, particularly in very low water subcooling (a few degrees).

II.2 FARO L-14

II.2.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 2 and 3.

II.2.b Relevance to reactor conditions: M

This test was performed using prototypic corium at high temperature. But ambient pressure was high (51 bars) so it may be relevant to in-vessel FCIs, but might not be relevant to reactor conditions if the primary system pressure is fully depressurised either by an initiating event of

LOCA or actuation of SDS to avoid DCH.

II.2.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.2.d Quality of data: H

The data have been well measured and documented.

II.2.e Unresolved discrepancies with previous calculations

This test had been extensively used in ISP-39 work and the predictions of various codes spread over unacceptable band.

II.3 FARO L-31

II.3.a Description of the experiment:

The major differences in the experimental conditions between L-14 and L-31 are melt jet diameter (100:50), initial pressure (51:2), water temperature (537:291). The details of the experimental conditions, summary of results, precise references can be found in Table 7 and References 1.

II.3.b Relevance to reactor conditions: H

This test was performed using prototypic corium at high temperature. The ambient pressure was low (2.1 bars) so it is highly relevant to reactor conditions.

II.3.c Level of characterisation of initial and boundary conditions: H

The initial and boundary conditions were relatively well defined, measured, and reported.

II.3.d Quality of data: H

The data have been well measured and documented.

II.3.e Unresolved discrepancies with previous calculations

No calculation.

II.4 Selection Criteria and Ranking for Pre-mixing case

Based on the discussions above, the conclusion of the ranking is summarized in the table below.

Table 5. Pre-mixing Ranking

	QUEOS-32	L-14	L-31
Relevance to reactor conditions	L	M	H
Quality of data	H	H	H
Level of characterization of initial conditions	H	H	H
Used Material	ZrO2	UO2/ZrO2 (8:2)	UO2/ZrO2 (8:2)
Unresolved discrepancies with previous calculations	Phase change	ISP-39	
Comments	Solid balls		

III. RELEVANT EXPLOSION EXPERIMENTS

As discussed in section 1, the highly ranked parameters for the prototypic condition are the melt composition, melt mass, pool geometry and environmental pressure.TROI-13 matches all these criteria best. Though KROTOS-44 is a very nice set of test for explosion calculation, it might not be relevant to the reactor conditions, for Alumina was used instead of prototypic material. KROTOS-37 is a typical explosion experiment using prototypic melt. However, it did not lead to an energetic explosion. The initial and boundary conditions for those three experiments are listed in Table 7. Table 6 lists the results of explosion ranking for the code comparison.

III.1 KROTOS: K-37

III.1.a Description of the experiment:

KROTOS-44 is a typical explosion experiment using a prototypic melt of UO_2 / ZrO_2 mixture at 80:20. The details of the experimental conditions, summary of results, precise references can be found in Table 7, References 6, and Reference 7

III.1.b Relevance to reactor conditions: M

The typical contact mode of ex-vessel steam explosion is at low-pressure, sub-cooled water, the diameter of melt jet at about 7 cm, water depth at about 1- 8 m, free fall height at about 1-8 m.

Two conditions are rather far from typical ex-vessel FCI mode. The first one is the melt geometry. To simulate the prototypic condition, we should simulate a melt jet of 7 cm in 1 m pool, which requires about 31 kg of corium. So, melt jet diameter and amount of melt is rather different from typical ex-vessel condition. The second one is the pool geometry. The ratio of the cross sectional area is one of the major parameters influencing the premixing and explosion behaviour, as it provides water volume for the melt water interaction and flow area for the venting of steam generated from the leading portion of the melt jet. So, it needs to be preserved in the experiments.

The test section of the KROTOS is a kind of one-dimensional shape, where a cylindrical test section with a 200mm inner diameter is used. The initial jet diameter in the KROTOS experiment is about 30 mm, which leads to a water to fuel ratio of 30 in terms of the cross sectional area. The typical ex-vessel FCI mode provides much bigger water to melt cross-sectional area ratio. The ranking is M.

III.1.c Level of characterisation of initial and boundary conditions: L

Though it is not clear whether melt jet is well maintained by the melt delivery mechanism used in the KROTOS, initial and boundary conditions are well defined. However, K-37 did not result in energetic reaction, so it is not suitable for the code calculation. The ranking is L.

III.1.d Quality of data: H

The quality of JRC data is excellent. The ranking is H.

III.1.e Unresolved discrepancies with previous calculations: Yes

There were discussions and code comparisons [7] on the role of hydrogen generation for the non-explosive nature of the tests. It is not clear whether hydrogen generation was measured for the K-37 test.

III.2 KROTOS: K-44

III.2.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7, References 6, and Reference 7

III.2.b Relevance to reactor conditions: L

It is Alumina test and it has similar test conditions as those of K-37. As the effect of material is the least understood part of the steam explosion model, it might be not relevant to the reactor condition. The ranking is L.

III.2.c Level of characterisation of initial and boundary conditions: L

As it has similar test conditions as those of K-37, the ranking is L.

III.2.d Quality of data: H

The quality of JRC data is excellent. The ranking is H.

III.2.e Unresolved discrepancies with previous calculations: No.

The code predictions and results of code calculation agree reasonably. However since the material used was Alumina, it cannot address the effect of material property.

III.3 TROI-13

III.3.a Description of the experiment:

The details of the experimental conditions, summary of results, precise references can be found in Table 7, Reference 4, and Reference 5

III.3.b Relevance to reactor conditions: H

The typical contact mode of ex-vessel steam explosion is at low-pressure, sub-cooled water, the diameter of melt jet at about 7 cm, water depth at about 1- 8 m, free fall height at about 1- 8 m.

To simulate the prototypic condition, we should simulate a melt jet of 7 cm in 1 m pool, which requires about 31 kg of corium. As the amount of melt is about 7 kg and the melt jet diameter is 2 cm. So, it is rather far from typical ex-vessel FCI mode. As the initial melt jet diameter of this test is about the same as that of KROTOS, TROI provides much bigger water to melt cross-sectional area ratio. It is better in terms of preserving ratio of cross sectional area of melt and water. The ranking is H

III.3.c Level of characterisation of initial and boundary conditions: M

TROI-13 resulted in a spontaneous steam explosion. The dynamic pressure, impulse, pressure and temperature responses of the test section and containment chamber were measured. The initial and boundary conditions are well defined. As the response of the system is rather multi-dimensional, there might be some difficulties in performing code calculations and in comparing the results with experimental results. The one-dimensional pressure propagation cannot be simulated. The ranking is M.

III.3.d Quality of data: H

The quality of KAERI data is reasonable. The ranking is H.

III.3.e Unresolved discrepancies with previous calculations: Yes

As there was no code calculations for the TROI-13, there might be some discrepancies.

III.4 Selection Criteria and Ranking for Explosion case

Based on the discussions above, the conclusion of the ranking is summarized in the following table

Table 6. Explosion mixing

	K-37	K-44	TROI-13
Relevance to reactor conditions	M	L	H
Quality of data	H	H	H
Level of characterization of initial conditions	L	M	M
Used Material	H	L	H
Unresolved discrepancies with previous calculations	Yes	No	Probably
Comments			Modified T-13 could be much better

Table 7. Initial and Boundary conditions for the major SE experiments using Corium

	QUEOS-32	**L-31**	**L-14**	**TROI-13**	**K-37**	**K-44**
Melt Mass (kg)	14 (5 mm)	92	125	7.7	3.2	1.5
Composition (UO_2/ZrO_2)	ZrO2	80:20	80:20	70:30	79:21	Alumina
Melt Temperature (K)	1818	2990	3100	~3300 K	~3018	2625
Melt Release Diameter (mm)	100	50	Nozzle 100	20	Initial Jet 30	
Test Section Diameter (m)	0.7x0.7	0.71	0.71	0.6	0.2	0.2
Initial Pressure (MPa)	0.1	0.21	5.1	0.1	0.1	0.21
Atmosphere	Air	Ar	77% steam, 23% Ar	Air	He	NR
Free Board Volume (m^3)	0.68	3.54	1.26	8.03		NR
Melt Fall Height (m)	1.3	0.74	1.04	3.9	0.44	0.44
Water Depth (m)	1.0	1.45	2.05	0.67	1.105	1.3
Water Temperature (K)	372	291	537	292	294	295
Water Mass (K)	490	492	623	189	34.5	34.8
H2 Generation	NR	NR	NR	Negligible	NR	NR
Debris	NA	< 1mm, ~5%	< 1mm, ~5%	< 1mm, ~40%	1.4 mm mass mean	0.1 mm mass mean
Steam Explosion	No	No	No	Yes	No	Yes
Typical Data	Video Steam rate P	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T	Dome P/T Water T
Dynamic Pressure	Yes	No	No	Measured	No	Measured
Trigger	No	No	No	No	Yes	Yes
Reference	9	1	2,3	4,5	6,7	7,8

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OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in Npp's

NRC Contribution

I RELEVANT CONDITIONS FOR ENERGETIC FCI's IN NPP's

I.1 Alpha-Mode Containment Failure in PWRs

Relevant conditions (in a bounding sense) for alpha-mode containment failure in PWRs are tons of primarily oxidic melt pouring through the bottom of core support plate in single or a multiple jet configuration. The pour diameter is on the order of tens of centimeters. The water (coolant) in the lower plenum is usually saturated though some subcooling may be considered. Melt may be slightly superheated (~100 to 200^{o}K superheat). Melt to coolant volume ratio is in the range of 1:3 to 1:10. The lower internal structures in reactor pressure vessels vary from design to design. Therefore, melt jet configurations and melt mass distribution over a given area are also likely to vary from design to design. However, a phenomenological investigation with this level of details is not warranted since the alpha-mode containment failure had been determined to be not significant from a risk perspective. Rather, a phenomenological investigation in a bounding sense is deemed adequate. In that sense, an equivalent jet (pour) diameter on the order of 10 to 50 cm may be considered sufficiently prototypic.

I.2 Lower Head Failure from In-Vessel Steam Explosions

Relevant conditions for this type of failure are core meltdown sequences that lead to a side pour of primarily oxidic melt into the downcomer region at rates of hundreds of kilograms per second. As in the previous case, the melt may be slightly superheated and the coolant (water) in the lower plenum is saturated. A bottom pour (i.e., a jet release through a hole at the bottom of lower head) is, in theory, possible though all indications from the TMI-2 and other studies are that a side pour is more likely. Consideration of lower head failure from in-vessel steam explosions is relevant to both LWRs and AP600-like ALWRs. The latter design relies on in-vessel retention through external cooling and thus, conditions are somewhat different.

I.3 Ex-Vessel Steam Explosions

This category concerns both PWRs and BWRs and within each class of reactors, may be relevant to a broad range of designs. Relevant conditions for ex-vessel explosions are lower head failure (side or bottom) leading to a release of mixed melt (i.e., oxidic combined with a significant fraction of metallic melt). Quantities of melt will vary based on the opening size and a bounding estimate of the range is several hundred kilograms to several thousand kilograms. Both low and high pressure releases are possible, noting the latter release condition will result in melt dispersal thus reducing the likelihood of an energetic FCI. Depending on metal fraction, the melt may or may not be associated with a large superheat. The water in the cavity or the drywell is subcooled and the degree of subcooling is likely to vary from design to design. For ex-vessel steam explosions, the geometry is relatively open for many reactor configurations and typically provides a large aspect ratio both of which help vent explosion energy.

II RELEVANT PREMIXING EXPERIMENTS

There is no single experiment that incorporates the above relevant conditions to a sufficient degree that would allow direct scaling of experimental results to full-scale reactor conditions. However, experiments such as FARO, KROTOS, TROI, etc. provide information (to varying degrees) on one or more phenomena associated with different stages of FCI. This information is useful in modeling different aspects of the FCI process. The analytical tool can then be used for extrapolation to full-scale reactor conditions.

With the above in mind, experiments from FARO, KROTOS, and TROI series may be selected as representatives of relevant premixing experiments. Note, however, that these experiments lacked direct measurements of premixing, i.e., space-time evolution of volume fractions and length scales. These premixing characteristics were derived from integral measurements and, as such, may not be unique. Nevertheless, from the prototypic material standpoint, FARO and other experiments mentioned in this paragraph are considered relevant premixing experiments for the purpose of the SERENA program.

II.1 FARO Experiments

II.1.a *Description of the Experiment*s

The FARO experiments were conducted to determine the extent of quenching of a large-scale mass of molten fuel with saturated water under conditions that are comparable to TMI-2 related events. The melt consisted of 80 w/o UO_2 - 20 w/o ZrO_2 with a superheat of 100 - 150^{o}K and masses ranging from 10 kg to over 200 kg. The melt was released as a single jet under gravity and the pour diameter varied from 5 cm to 10 cm. The water pool was at a depth of 1 - 2 meters. The pool was saturated in all but one experiment. The system pressure in these experiments varied from 5 to 50 bars. The melt composition in one experiment (L11) had about 5 w/o Zr. The extent of melt quench was measured by pressure rise in a closed volume, temperature changes in the water and the gas mixture, and the water level swell. The extent of fuel-coolant mixing was derived from the integral quench data. The major finding of the test series was that the molten fuel did not quench completely at high pressures but generally, the quenching rate was a function of system pressure, pour rate, pool depth, and subcooling. In experiment L11, nearly complete quenching was observed, believed due to addition of metal in the melt composition. For the SERENA premixing exercise, FARO experiments L19 (deeper pool) and L31 (subcooled pool) are proposed. If the scope permits additional experiments, consideration may be given to L11.

II.1.b *Relevance to Reactor Conditions*

The FARO experiments were primarily designed to be a full-scale simulation of a 1-D slice of the light water reactor lower plenum without internal structure. Thus, pressure, water depth, melt composition, and temperature represented prototypic conditions. The melt pour rate was scaled in relation to the TMI-2 event.

II.1.c *Level of Characterization of Initial and Boundary Conditions*

The test series is characterized by well-defined initial and boundary conditions. Given that in the experiments only integral measurements were taken (and in this sense the experiments are considered integral in nature), the level of characterization is adequate.

II.1.d *Quality of Data*

The pressure history, temperature history, and level swell data are of high quality. However, it should be mentioned again that the information on premixing derived from these integral measurements may not be unique.

II.1.e *Unresolved Discrepancies with Previous Calculations*

One of the FARO experiments (L14) was used for the International Standard Problem exercise ISP-39. A number of codes were used in the exercise. An important finding from this exercise is that no single code predicted all attributes of premixing adequately well. This is not surprising since the premixing in FARO experiments was not directly evidenced; rather, it was inferred from integral measurements and, as such, suffers from non-uniqueness. When using different codes for prediction, it is possible that different premixtures (assumed or used in code calculations) will result in a good prediction for one attribute, but will produce a large scatter in other attributes. For these reasons, the purpose of the SERENA program will be best served if a subset of FARO experiments and perhaps, a few other experiments (e.g., KROTOS and TROI) are used for a comparative exercise. In this manner, premixture evolution in different code calculations that would produce consistent prediction of integral data, could be compared.

II.2 KROTOS Experiments

The KROTOS experiments were conducted to provide benchmark explosion data for prototypic as well as simulant materials. These experiments were conducted under controlled initial and boundary conditions, but at a much smaller scale than the FARO experiments. As already mentioned, the KROTOS experiments can be used as supplements to the FARO experiments in the SERENA premixing exercise. However, these experiments are more appropriate for the SERENA explosion exercise. For this reason, further description of the KROTOS experiments will be provided under the discussion of relevant explosion experiments.

II.3 TROI Experiments

Further description of the TROI experiments will be provided under the discussion of relevant explosion experiments.

III RELEVANT EXPLOSION EXPERIMENTS

III.1 KROTOS Experiments

III.1.a *Description of the Experiments*

The KROTOS experiments were conducted in three series, all at a small scale (up to about one liter of molten fuel) under controlled conditions. The first series used tin as a melt simulant; the second used aluminum oxide, and the third used prototypic urania-zirconia material. Most tests were conducted at one bar system pressure; in a few tests, the pressure was elevated up to about 4 bars. A wide range of melt superheat was used in the experiments for the purpose of generating a large data base. Likewise, a wide range of subcooling was used. The melt in KROTOS experiments was released as a single jet through a 30 mm nozzle. In all experiments, a triggering device, mounted on the bottom of the test section, was used to trigger the premixture. Dynamic pressures, water temperature, and level swell were measured in the experiments. Void fractions at triggering and conversion efficiency were derived from these measurements. Additionally, debris particle size distributions were computed from the post-test debris analysis.

In the tin series experiments, explosions were observed in all cases when the premixture was triggered whereas all alumina tests produced spontaneous explosions. In contrast, in the urania-zirconia series experiments, no explosions were observed in all one bar tests even when triggered. In a few elevated pressure tests, mild explosions were noted and the conversion efficiencies calculated were much too low. For the SERENA exercise, several KROTOS experiments are proposed to cover two important attributes: simulant variation i.e., alumina vs. urania-zirconia, and pressure variation (one bar vs. elevated pressure). Specifically, the KROTOS experiments K38 (alumina), K45 (prototypic melt), K58 (prototypic melt and elevated pressure) are proposed for the explosion exercise. The last of these experiments, K58 complements the set of FARO experiments for the premixing exercise since in K58, better visual observation of melt-water mixing was recorded.

III.1.b *Relevance to Reactor Conditions*

Unlike the FARO experiments in which a large number of attributes represented reactor prototypic conditions, the KROTOS experiments are prototypic only in terms of melt material and melt temperature. Realizing, however, that the principle objective of KROTOS experiments is to investigate the explosivity of prototypic melt and to determine if an explosion event would be sufficiently energetic to compromise in-vessel retention or ex-vessel coolability, these experiments are the closest to serve the purpose of the SERENA exercise.

III.1.c *Level of Characterization of Initial and Boundary Conditions*

The test series is characterized by well-defined initial and boundary conditions. Given that in the experiments only integral measurements were taken (and in this sense the experiments are considered integral in nature), the level of characterization is adequate.

III.1.d *Quality of Data*

The dynamic pressure trace, temperature history, and level swell data are of high quality. However, it should be mentioned again that the information on premixture evolution is not directly evidenced in these experiments. The information is derived and, as such, subsequent wave dynamics calculations performed by codes may not be unique.

III.1.e *Unresolved Discrepancies with Previous Calculations*

It follows from the discussion in the previous paragraph that there will likely be discrepancies in explosion calculations unless consistencies in deriving premixture evolution are assured to a large extent. In this respect, FARO premixing calculations under the SERENA mixing exercise and KROTOS premixing calculations as part of the overall explosion calculations will serve an important role in assuring consistencies. It is for this reason we recommend a number of KROTOS experiments specified above and additionally, TROI experiments and perhaps other explosion experiments. We further note that one can perform a complimentary set of explosion calculations with FARO premixtures to generate explosion data assuming the mixtures are triggerable. Alternatively, if the mixtures cannot be triggered, one can make a conclusive statement about the triggerability of a representative mass of prototypic melt.

III.2 TROI Experiments

III.2.a *Description of Experiments*

With the premature termination of the KROTOS program, the Korean Atomic Energy Research Institute (KAERI) initiated in 1997 its own FCI program, Test for Real COrium Interaction with Water or TROI. This program has the same objectives as the KROTOS program, i.e., to investigate the explosivity of prototypic reactor melt and to provide benchmark explosion data for such melt. Two series of tests were conducted thus far. In the first series, several kilogram quantities of zirconia melt was used whereas in the second series, similar quantities of urania-zirconia melt was used. The jet diameter in the tests varied as did melt superheat and water subcooling. Among six tests in the first series, three (TROI-3, 5 and 6) reported to have spontaneous explosions. An interesting finding from two of the three tests which had spontaneous explosions is that larger the released melt mass, larger is the dynamic pressure. Among five tests in the second series, three (TROI-12, 13 and ??) reported to have spontaneous explosions. Data analysis by KAERI is currently in progress to shed further light into this important finding that the prototypic reactor melt can indeed be explosive under certain conditions. For the purpose of the SERENA exercise, we propose TROI-13 assuming that relevant data from this experiment will be made available.

III.2.b *Relevance to Reactor Conditions*

Since the TROI experiments are essentially KROTOS experiments with some parametric variations, statements made under this heading for KROTOS experiments apply equally to TROI experiments. Additionally, TROI experiments are relevant to reactor conditions since these experiments have shown for the first time that the reactor prototypic melt can be explosive with a comparable conversion efficiency (as reported by KAERI) to that of alumina and other simulant melts.

III.2.c *Level of Characterization of Initial and Boundary Conditions*

The level of characterization of initial and boundary conditions is not nearly as good, according to the documented reports. For example, the melt temperature reported appears to have a very high degree of superheat. However, the uncertainties in temperature measurements may also be very large. In some experiments, the initial jet diameter is not known. For the SERENA exercise, this level of characterization will pose some challenges but will not be insurmountable.

III.2.d *Quality of Data*

Similar remarks to those made previously in connection with the KROTOS experiments apply here as well. Additionally, since not enough information is documented yet in the open literature, further judgement cannot be made regarding the quality of data.

OECD RESEARCH PROGRAMME ON
FUEL-COOLANT INTERACTION

SERENA

TASK 1

Identification of Relevant Conditions and Experiments for FCI in Npp's

VTT Contribution

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Summary

The interest for current Finnish reactors is focused on ex-vessel steam explosions. The severe accident management strategy for the Westinghouse Atom BWRs requires filling of the lower drywell beneath the reactor pressure vessel with coolant from the suppression pool prior to vessel failure. This may lead to energetic FCI in the lower drywell. Fragmentation (premixing) experiments taken from public sources have been ranked against the expected conditions of this sequence. No ranking has been made of steam explosion experiments.

1. RELEVANT CONDITIONS FOR ENERGETIC FCI IN THE OLKILUOTO BWR

1.1. The Base Case

Based on plant calculations [Lindholm et al., 1997], the most likely failure mode of the Olkiluoto pressure vessel is an instrument tube penetration. The inner diameter of an instrument tube is 7.1 cm and there are a total of 50 instrument tube penetrations in the pressure vessel lower head. The jet diameters of the FARO experiments coincide well with the Olkiluoto reactor case.

If the pedestal flooding is successfully carried out, about 518 m^3 of water has drained into the pedestal prior to the discharge of core melt. The corresponding water pool height is 8.3 m and water mass 513 000 kg. The temperature of water in the pedestal sump is 319 K and the pressure in pedestal is 1.01 bar.

The ratio of corium mass vs. water mass in Olkiluoto plant is 0.38, which is close to that in FARO test L-28. The water in Olkiluoto pedestal is sub-cooled by 56 degrees. The pool heat sink (before the pool starts to boil) is enough to quench about 57 % of the whole corium mass, if energy is entirely used for heating of the pool.

The debris discharge velocity in Olkiluoto is estimated 6.7 – 14.2 m/s [Lindholm, 2000]. If the instrument tube nozzle ablation is ignored ($\varnothing_{tube}$ = 0.071 m) and the average corium density of 8800 kg/m^3 is assumed, the estimated mass flow rate through one penetration will be 233-495 kg/s. According to the model developed by Pilch [Summers et al, 1994] the area of the instrument tube penetration in lower head of Olkiluoto pressure vessel would grow to ten times the initial area in 13 s. Taking this growth into account, the debris discharge rate would be 2334 – 4947 kg/s. The average discharge rate during the first 13 s of the pour would be 1283 –2721 kg/s. With the discharge rate of 2721 kg/s the pool would be saturated in 28 s. After a 28 s pour of the melt, the debris/water ratio would be 0.15, which is rather close to that in the KROTOS (0.11) and the FARO experiments L-31 and 33 (0.16 and 0.19).

The final velocity of debris at the water surface of the pedestal pool is 15 - 22 m/s. This is at least twice the velocities applied in the available tests.

1.2. Some Uncertainty Considerations

If 50 % of the zirconium inventory of the core is oxidised, the core melt at the bottom head contains about 25 % metals (Zr + steel) and 75 % oxides (UO_2+ ZrO_2). If one assumes a rapid lower head failure following the corium arrival to the lower head, only the steel component is in liquid form according to MELCOR calculations. The total molten material mass from Olkiluoto lower head during the first seconds would be 153-330 kg of metal. With average discharge rate 2721 kg/s a total of 76 200 kg of melt would be discharged during 28 s. If 25 % of this is metallic, which is assumed to fragment into fine particles, the mass of fine fragments would be 19 050 kg.

1.3. The important parameters

Based on the discussion above, the most interesting conditions derived from the scenario are (see also Tables 1 and 2 below):

1. Pressure should represent containment conditions, 2-6 (10) bars
2. Water should be subcooled
3. Melt-coolant mass ratio should be close to 0.2

2. RELEVANT PREMIXING EXPERIMENTS

The values of the key parameters that have been observed to affect most the melt fragmentation history and some experiments reported in the literature are gathered in Table 1.

Table 1. *Key parameters affecting the debris fragmentation. Comparison of conditions in different experiments and in Olkiluoto plant.*

Test	P [bar]	T_{water} [^oC]	jet diameter [mm]	debris/ coolant mass ratio	velocity at water surface [m/s]	comments
Spencer, Gabor & Cassulo	1.013	25 or 100	N/A	0.08	N/A	simulant
ALPHA	1.013	50	30		3.5	simulant metal mixture
EJET-tests	1.013	30 or 88	38, 76 or 163	0.08 – 0.1		simulant Fe-Al_2O_3
MIRA-20, 21, 22 tests	1.013	25, 50, 75 or 95	25	0.07	3 or 6	simulant binary oxide
CWTI-9 and CWTI-10	1.413 1.813	94 25	22 25.4	0.23 0.12	3.17 4.09	corium (oxide + 24 % metal)
CCM-1 CCM-2 CCM-3 CCM-4 CCM-5 CCM-6	1.1 1.75 3.13 3.55 1.34 2.02	57 99 100 63 55 101	25.4 20 25.4 50.8 50.8 50.8	0.06 0.51 0.09 0.24 0.022 0.025	3.4 5.3 8.2 8.7 2.6 5.6	corium (oxide+24 % metal)
FARO L-24 L-27 L-28 L-29 L-31 L-33	5 5 5 2 2 4	152 151 151 4 18 20	10 10 5 5 5 5	0.25 0.24 0.33 0.08 0.19 0.16	11.2 10.8 11.0 6.4 6.4 11.5	corium oxide
KROTOS K-56 K-58	3.7 3.7	18 18	30 30	0.11 0.11	30 30	corium oxide
Olkiluoto reactor	3-10	50-100	71-213	0.16	13-23	oxide + metal

In consideration of these aspects, 6 tests have been selected for closer analysis to find a representative particle size distribution for Olkiluoto case (Table 2).

Table 2. Comparison of experiments that are considered representative for Nordic BWR applications.

Test	P [bar]	T_{water} [^oC]	jet diameter [mm]	debris/ coolant mass ratio	velocity at water surface [m/s]	comments
L-24(1	5	152	10	0.25	11.2	corium oxide
L-31(2	2	18	5	0.19	6.4	corium oxide
CCM-1(3	1.1	57	25.4	0.06	3.4	corium
CCM-3(4	3.13	100	25.4	0.09	8.2	corium
CCM-5(5	1.34	55	50.8	0.022	2.6	corium
MIRA-20(6	1.013	25	25	0.07	3	simulant
Olkiluoto	3-10	50-100	71-213	0.16	13-23	oxide + metal

(1 suitable system pressure and jet velocity, saturated water pool, corium test

(2 slightly low system pressure and jet velocity, subcooled water, applicable debris/coolant ratio, corium test

(3 subcooled water, low pressure and jet velocity, corium contains also metals

(4 saturated water, applicable pressure and jet velocity, low debris/coolant mass ratio

(5 subcooled water, low pressure and jet velocity, larger scale than in CCM-1

(6 representative simulant test, representative water subcooling, jet velocity and debris density.

3. RELEVANT EXPLOSION EXPERIMENTS

We do not have such expertise that we could make ranking on this aspect.

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