Introduction to Final Results of OECD SERENA Project on Steam Explosion

Seong-Wan Hong [a*], Pascal Piluso [b],) Sudhamay Basu[c]
a) Korea Atomic Energy Research Institute
b) CEA, cea.fr pascal.piluso@cea.fr
c) USNRC, Sudhamay.Basu@nrc.gov
[*]*Corresponding author: swhong@kaeri.re.kr*

1. Introduction

The OECD/SERENA project was launched from the outcome of the WGAMA/SERENA activity (2001-2006), which indicated that voiding (gas content and distribution) in pre-mixture and also corium melt properties as well as uncertainties therein were the key issues to be resolved to reduce the scatter of the calculated steam explosion loads to an acceptable level. The WGAMA/SERENA activity concluded that while the scatter of the calculated in-vessel steam explosion loads is large, there is also a large safety margin between the upper bound of the calculated loads and the failure strength of the reactor pressure vessel. Thus, taking into account the uncertainties, an in-vessel steam explosion, in all probability, would not challenge the integrity of the vessel and hence the containment. On this basis, the in-vessel steam explosion issue was considered adequately resolved from a risk perspective. However, the large scatter in calculated ex-vessel steam explosion loads was such that in some cases, the calculated loads far exceeded the failure strength of the containment. The large scatter in steam explosion loads was attributed to a lack of precision in modeling jet breakup and voiding in pre-mixture, as well as the lack of a better understanding of the role of corium material properties.

The OECD/SERENA project (sometimes referred to as SERENA Phase II programme) was formulated to resolve the uncertainties on the above issues by performing a limited number of well-designed tests with advanced instrumentation for measuring spatial distribution of voids, among other things, and using a spectrum of melt compositions and initial and boundary conditions which are representative of ex-vessel scenarios.

The final result of the OECD-SERENA Phase 2 project for the resolution of ex-vessel steam explosion risks will be described in this paper.

2. Results of the SERENA Project

2.1 Experimental Program

The objectives of the experimental program were to provide data: (1) to clarify the explosion behaviour of prototypic corium melts and for validation of explosion models for prototypic materials; and (2) for steam explosion behavior in two different geometries to verify the geometrical extrapolation capabilities of the codes. These objectives were to be accomplished by conducting complementary experiments at two different facilities: KROTOS at the Commissariat l'Energie Atomique des aux Energies Alternatives (CEA) in Cadarache, France, and TROI at Korea Atomic Energy Research Institute (KAERI) in Daejon, Korea. The proposed test matrix, as shown in the table 1, is composed of two series of complementary tests: one in one-dimensional KROTOS configuration with 5 kg of melt, and the other in multi-dimensional TROI configuration with 20 kg of melt.

The KROTOS facility features one-dimensional behaviour of mixing and explosion propagation, and allows a clear characterisation of mixing (melt and void distribution), escalation, and propagation behaviour. TROI is more suited for testing the FCI behaviour in multi-dimensional geometry. The wider test section in TROI allows more prototypic sideways spreading of the mixing region (void and melt) and multi-dimensional pressure wave propagation.

Table 1. Experimental grid

n°	Objective	TROI	KROTOS
1	Challenging conditions Mat 1: 70 wt%UO_2-30 wt %ZrO_2 Vessel: 0.4 MPa- 273K	TS-1 Melt superheating Thick jet	KS-1 Melt superheating Thin jet
2	Geometry effect Mat 1: 70 wt%UO_2-30 wt%ZrO_2 Vessel: 0.2 MPa- 333K	TS-2 2 D Jet diameter: 50 mm	KS-2 1D Jet diameter: 30 mm
3	Reproducibility test-Idem test 2 Mat 1: 70 wt%UO_2-30 wt%ZrO_2 Vessel: 0.2 MPa- 333K	TS-3 Idem test 2	KS-3 Idem test 2
4	Material effect: oxide composition Mat 2: 80 wt%UO_2-20 wt %ZrO_2 Vessel: 0.2 MPa- 333K	TS-4 Melt superheating Thick jet	KS-4 Melt superheating Thin jet
5	Material effect: sub-oxide composition and oxidation Mat 3: 70 wt%UO_2-15 wt%ZrO_2-15 wt%Zr Vessel: 0.2 MPa- 333K	TS-5 Melt superheating Thick jet	KS-5 Melt superheating Thin jet
6	Material effect: oxide composition and large interval of solidification Mat 4: 70 wt %UO_2-30 wt %ZrO_2 +Fe_2O_3+Low volatile Fission Products Vessel: 0.2 MPa- 333K	TS-6 Melt superheating Thick jet	KS-6 Melt superheating Thin jet

2.2.1 Test facilities

The KROTOS and TROI test facilities are shown in Figure 1. The strength of using both KROTOS and TROI is to be able to check the key effects in experiments with increasing complexity and to check whether a consistent interpretation of both KROTOS and TROI with identical modelling approaches is possible. Validation of models on KROTOS data and a verification of the code capabilities to calculate more reactor-oriented situations simulated in TROI strengthens our confidence in the code applicability to reactor conditions.

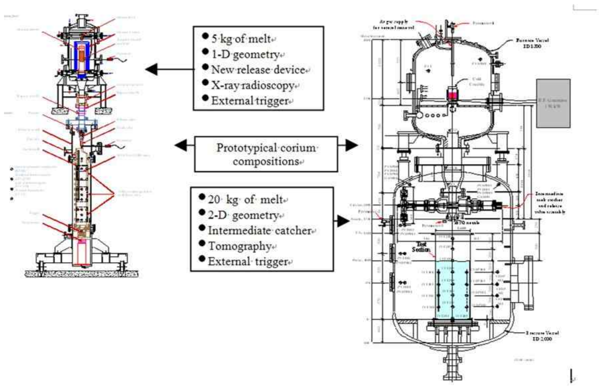

Figure 1. KROTOS and TROI test facilities

2.2.2 Experimental Results

The steam explosion efficiency (expressed in terms of conversion ratio in the table 2) in all tests is rather low, spanning a range between nominally 0.1% or less to no more than 0.7% (generally higher in TROI tests than in KROTOS tests).

Table 2. Main results of experimental tests

Test ID	TS-1	TS-2	TS-3	TS-4	TS-5	TS-6
Delivered Melt Mass (kg)	15.4	12.5	15.9	14.3	17.9	9.3
Melt Temperature (K)	~3000	3063	3107	3011	2940	2910
Melt Superheat (K)	145	228	272	171	140	239
Melt Composition (wt%) UO_2-ZrO2 Zr U Fe_2O_3 FP	73.4/26.6	68.0/32.0	71.0/29.0	81.0/19.0	76.0/18.3 5.0 0.7	73.3/18.5 4.9 3.3
Water Depth (m)	1.0	1.0	1.0	1.0	1.0	1.0
Water Temperature (K)	301	334	331	333	337	338
Sub-cooling (K)	115.9	61.7	65.1	64.0	57.7	56. 9
System Pressure (MPa)	0.4	0.2	0.2	0.2	0.2	0.2
Fall Distance (m)	1.0	1.0	1.0	1.0	1.0	1.0
Jet Diameter (mm)	50	50	50	50	50	50
Triggering Time After Release (ms)	939	875	.875	1 040	1 046	1 050
Location of Melt Leading Edge at T rigger Time (m)	~0.3	~0.4	~0.4	~0.4	~0.1	~0.4
Void at Triggering (vol %)	~4	~3	~2	14-24	12-34	4-10
Max. Pressure (normalized)	0.85	0.5	0.6	1.0	0.35	1.25
Impulse (normalized)	0.75	>0.9	~1.0	>>1.0	0.5	>>1.0
Steam Explosion	S/E	S/E	S/E	S/E	Steam Spike	S/E
Conversion Ratio (normalized)	0.34	0.8	0.63	1.0	0.17	1.89

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This observation may be somewhat counter-intuitive given than KROTOS tests are one-dimensional in nature and thus, are expected to yield higher efficiency relative to multi-dimensional TROI tests. The observation, however, is supported by the trend in void fraction evolution in TROI and KROTOS experiments. Specifically, KROTOS tests showed higher void fractions than the TROI tests. Note the void fractions were measured in the two facilities using different measurement techniques: in the KROTOS facility using an X-ray Linatron device whereas in the TROI facility, using a differential pressure transducer system. There are also differences in the methods by which the conversion ratios were computed in the two series of tests. These differences and perhaps others are likely to introduce uncertainties in the measured and computed values. Further analysis of test data accounting for uncertainties is highly recommended.

Another important observation from the experimental results relates to the explosivity of “eutectic” melt compositions. In previous TROI tests, 70 w/o UO2– 30 w/o ZrO2 melt composition (so-called “eutectic”) was found to be more explosive than 80 w/o UO2 -20 w/o ZrO2 melt composition (so-called “non-eutectic”), all the other experimental conditions except melt temperature being similar. So it was thought that the energetics of steam explosion was linked to the nature of the corium melt, i.e., eutectic melt with little to no solidification interval produces higher energetics than non-eutectic melt with larger solidification interval. This finding could not be corroborated in the OECD/SERENA Project. In fact, an inverse behaviour for energetics was observed for experiments in both TROI and KROTOS facilities whereby 80 w/o UO2 -20 w/o ZrO2 melt composition produced somewhat higher energetics than 70 w/o UO2– 30 w/o ZrO2 melt composition. Thus, it is concluded that the effect previously observed concerning the difference in explosion behaviour between oxidic eutectic and oxidic non-eutectic melt compositions seems no longer supported. This is further corroborated by analytical work.

Other important observations from KROTOS and TROI experiments in the framework of the OECD/SERENA project are:

1)Prototypic core melt (i.e., predominantly a mixture of UO2 and ZrO2) does not produce strong explosion energetics relative to simulant melt compositions (i.e., KROTOS alumina tests) even though the calculated energetics in some TROI and KROTOS tests in the current series were higher than in the previous experiments with prototypic mixtures. The current series, in this regard, provide further confirmation of low steam explosion energetics of prototypic melt.

2) Some differences between TROI and KROTOS results are noted for melt compositions that are not fully oxidic (i.e., mixed melt with oxide, metal, and other components). The TROI test with metal in the melt composition highlighted possible importance of hydrogen production due to oxidation of metal, but did not quantify these effects. The KROTOS test, on the other hand, was not as conclusive about the role of hydrogen. Another difference noted was with regard to conversion efficiency between the counterpart tests. Experiments with rigid constraints (KROTOS) appear to produce lower conversion efficiencies (calculated)

than those with less rigid constraints (TROI). Such differences, which appear to be counterintuitive, require further investigation.

3) KROTOS and TROI results generally show consistent behavior at two different geometric scales indicating the results may be extrapolated to reactor scale with appropriate uncertainty considerations.

4) KROTOS and TROI experiments were instrumented with advanced instrumentation. These experiments produced both local and global data of interest, in particular, local void and melt distribution data for code assessment and improvement. The substantive amount of data generated in the experiments has not been fully explored yet. Also, no attempt has been made thus far to quantify the uncertainties in experimental data or calculated energetics.

2.2 Analytical Program

The analytical programme was aimed at complementing the analytical work in WGAMA/SERENA activity, completed in 2006, by integrating the results of the experimental programme in the current phase, and by updating the capabilities of the FCI models/codes for use in reactor safety analysis. The programme consisted of the following specific tasks: 1) Perform pre-test calculations in support of test specifications, and post-test calculations in support of data analysis and code assessment; 2) Organise a benchmark exercise with "blind pre-test" calculations for one test; 3) Improve the understanding of those key phenomena that are believed to have major influence on the FCI process; Address the scaling effect and application to the reactor case; 4) Give specific attention to the link between FCI models/codes and general system codes (e.g. COCOSYS) or integral codes (e.g. ASTEC, MELCOR); and Demonstrate the progress made in the OECD/SERENA project as compared with WGAMA/SERENA activity, by repeating the "ex-vessel reactor exercise."

2.2.1 Analysis Tools

The results of the first five tasks above are documented in a companion report which constitutes one of the main deliverables of the OECD/SERENA project namely, a report summarising the analytical activities. The report focuses on phenomenological understanding and modeling aspects and improvements therein, covering the phenomena of jet fragmentation, voiding, melt solidification, and explosion propagation, as informed by pre-test and post-test calculations. Emphasis is placed on improvement of phenomenological understanding based on new information generated either by the experimental part of the OECD/SERENA project or by other sources since the completion of the WGAMA/SERENA activity. Also, emphasis is placed on informing the FCI analytical tools and reaching a convergence in FCI modeling, to the extent feasible, thereby reducing the scatter in calculated steam explosion loads and increasing the confidence in code capabilities for reactor applications. The last task and the results therein are documented in a second companion report which constitutes another main deliverable, i.e., the ex-vessel exercise synthesis report. This task and its results will be summarized in a separate section below.

The aim of the analytical activities was, among other things, to improve the common understanding of those key phenomena that are believed to have a major influence on the FCI process and steam explosion behaviour, and to investigate the scaling effect for the purpose of reactor applications. Emphasis was placed in particular on jet fragmentation, voiding, and corium properties as they relate to occurrence and propagation of steam explosion. In discussing the progress, emphasis was placed on improvement of phenomenological understanding based on new information generated either by the experimental part of the OECD/SERENA project or by other sources since the completion of the WGAMA/SERENA activity. Also, emphasis was placed on reaching a convergence in FCI modeling in various codes, to the extent feasible, and reducing the scatter in calculated steam explosion loads thereby increasing the confidence in code capabilities for reactor applications. The codes used in the present exercise were MC3D (developed by IRSN-CEA), JASMINE (developed by JNES), JEMI-IDEMO (developed by IKE), TEXAS-V (developed by UW) and TRACER-II (developed by KMU).

2.2.2 Analytical Results

Important observations and conclusions from the analytical activities carried out in the OECD/SERENA project are delineated below:

1) FCI codes improved, some more than others, during the course of the SERENA project. In general, the code predictions are in reasonable agreement with the data obtained in KROTOS and TROI experiments. However, the codes have not been assessed against the full spectrum of new experimental data. Analytical work should continue in this area.

2) Melt solidification is recognized as a major contributor to the limitation of energetics for oxidic corium melts. Attempts to incorporate the solidification effect in FCI codes led to important model improvements, e.g., modeling of crust formation and its impact on fine fragmentation, and modeling of drop size distributions to capture effect of different solidification times. There is a need to confirm the limiting effect of solidification for a wider range of materials, especially prototypical core material with large liquidus-solidus temperature interval. There is also a need to improve the solidification modeling with regard to its effect on

suppressing fine fragmentation.

3) Jet fragmentation, recognized as a key phenomenon that determines the amount of melt mass participating in explosion, still needs improvements in modeling if uncertainties in energetics are deemed important for a specific safety application.

4) Melt density as a material property is considered by some analysts to be a key parameter in explaining the material effect on explosion energetics in previous KROTOS experiments. The high melt density of prototypic core melts yields smaller droplets, thus faster solidification and higher voiding. This may explain the lower energetics of the explosion with prototypic melts.

5) Other effects related to chemical interactions could be present but are thought to be of secondary importance. Modeling of oxidation effects in codes is at an initial state of development and lacks experimental data for validation. The role of oxidation and the need for adequate modeling should be carefully examined for melts containing metal which may be more prototypic in reactor scenarios.

6) Less effort has been put into specific modeling aspects of the explosion phase in the last several years. Work has been initiated recently on modeling of fine fragmentation.

2.3 Reactor Application

Important observations from the reactor application exercise are: A better consistency of the predictions of ex-vessel steam explosion was achieved among the various FCI codes used in the OECD/SERENA Project reactor synthesis exercise.

The calculated loads are somewhat less than those reported in the WGAMA/SERENA reactor exercise, perhaps a consequence of different input and boundary conditions. Nevertheless, there is still a large scatter in calculated loads.

The large scatter was attributed previously to an incomplete understanding of the effect of voiding. It is now believed that jet fragmentation plays a more important role, and that a more accurate modeling of fragmentation, using new data from KROTOS and TROI experiments, may help resolve the discrepancies between various code predictions. Melt solidification is another factor that may also play an important role in this respect.

There is still an outstanding issue concerning FCI code predictions at the reactor scale, stemming primarily from the basis of extrapolating the experimental results to reactor scale. It is believed that while the voiding phenomena (in ex-vessel cases) may not play a significant role at the experimental scale, its importance at the reactor scale cannot be ruled out.

3. Conclusions

The OECD/SERENA project accomplished in large part its stated objectives. The project generated new experimental data (in TROI and KROTOS facilities) for development of new phenomenological models, improvement of existing models, and assessment of FCI codes. TROI and KROTOS experiments provided further confirmation of low steam explosion energetics of prototypic melt even though the calculated energetics in some TROI and KROTOS tests in the current series were higher than in the previous experiments with prototypic mixtures. The project also provided new insights into FCI phenomena to improve the technical basis for regulatory decision making. However, it would be sometime before the insights can be fully integrated into new and improved models and codes.

Several new insights were also gained from the experiments including the significance of eutectic vs. non-eutectic melt composition, importance of oxidation and hydrogen production in melt containing metal, and the role of melt solidification in steam explosion energetics. The experiments also showed that melt superheat and coolant subcooling have limited impact on steam explosion energetics.

The experiments produced both local and global data of interest, in particular, local void and melt distribution data for code assessment and improvement. The substantive amount of data generated in the experiments has not been fully explored yet. Also, no attempt has been made thus far to quantify the uncertainties in experimental data. This should be pursued as a follow-on activity. Particular attention should be paid to analysis of void fraction data in the respective test facilities, noting in particular the formation and dissolution of localized voiding evidenced in the radioscopic measurements in the KROTOS facility. Attention should also be paid to calculated conversion ratios in the respective facilities with particular focus on the consistency between the calculation methods.

A good deal of analytical work was done in the OECD/SERENA project and this work aimed to improve the FCI models and codes using the data generated in the experimental part of the project. Admittedly, the analytical work was not able to take advantage of the full set of experimental data as the last experiment was conducted only at the end of the project. Nevertheless, the work attempted to reach a convergence of understanding on the role of various FCI attributes (e.g., jet fragmentation, voiding, melt solidification, melt properties, etc.) in estimating steam explosion potential and energetics of prototypic reactor materials. The outcome of the analytical work did not reveal anything that would contradict the current understanding of the role of the above attributes in steam explosion energetics.

In general, FCI codes have improved and code predictions are in reasonable agreement with the data obtained in KROTOS and TROI experiments. Better consistency was achieved among the various FCI codes in the prediction of ex-vessel steam explosion, and the calculated loads were somewhat less than those previously reported though there remains still a large scatter in the prediction of ex-vessel steam explosion loads. In that sense, the project did not provide a definitive resolution of the ex-vessel steam explosion issue.

Notwithstanding the progress made in the SERENA project, certain aspects of FCI and steam explosion research would continue to require further attention. The analytical work thus far confirms that a good understanding of the jet fragmentation process is key to developing robust FCI models which can fully explain the difference in steam explosion behaviour of different melts. The jet fragmentation/breakup physics is admittedly a complex subject requiring considerably more investigation to assure high fidelity modelling. However, for practical application of FCI codes and considering risk perspective, there appears to be a consensus towards a simplified approach based on consideration of some type of global fragmentation correlation.

The FCI codes have not been assessed against the full spectrum of new experimental data. Analytical work should continue in this area as it is believed that the new experimental data will be useful in improving further the FCI models and codes, which may help resolve the discrepancies between various code predictions. There are also other issues such as scalability of small-scale experimental results to reactor applications, development of new phenomenological models, and further improvement and assessment of multidimensional FCI codes. Particular attention should be paid to melt solidification modeling. Also, modelling of the pressurization process at high pressures needs further improvement.

Finally, it should be noted that the FCI models and codes can only be as precise as the experimental data supports and there are inherent uncertainties in experimental data. While from a regulatory and risk perspective, a "fit-for-purpose" code may be adequate, a sustained modeling and code development strategy is encouraged to improve the knowledge base and increase confidence in using the codes.

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