A benchmark exercise on an alternative TMI-2 accident scenario

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Abstract

In the frame of the OECD/NEA Working Group GAMA a benchmark problem was conducted in order to determine the ability of current advanced codes to predict core degradation in nuclear reactors. For this purpose, the TMI-2 reactor was selected with a well defined core degradation scenario following a small hot leg break, specified with simple initial and boundary conditions so that the influence of uncertainty of these conditions was minimized.

The benchmark sequence can be divided in three parts. For the initial transient, up to the primary system pumps trip, the calculated results are in good agreement. For the degradation phase, up to the reflooding of the core, the results show also a rather good agreement among all participants for global results like total hydrogen production and total mass of molten materials. The variability in these results is comparable or even better than the variability obtained in recent benchmarks on integral tests. In the final phase, the reflooding phase, some results may be questionable as they are apparently in contradiction with experimental findings and with the TMI-2 assumed evolution. Sensitivity studies performed by parti-

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cipants have shown that variations of some key empirical models could induce variations in calculated results of a single participant, which are of the same order of magnitude as the variation obtained when comparing different codes and/or participants. This indicates that some physical processes are still poorly known and inadequately modelled.

In summary, the results show a strong robustness of the current codes and a good agreement with large parts of the proposed alternative TMI-2 sequence. That is an evidence for the considerable progress made within the last 20 years.

Keywords

Severe accidents, In-vessel core degradation, Thermal-hydraulics, Accident analysis, Code development

1. Introduction

The experimental database on core degradation and melt relocation is limited to small-scale experiments which are only partially representative of what could occur in a reactor. Hence, there is uncertainty in the capability of codes to predict core degradation in postulated severe accident transients of nuclear power plants. Therefore, the OECD/NEA GAMA (Working Group on the Analysis and Management of Accidents) has launched an action in order to determine the ability of current advanced codes to predict core degradation in nuclear reactors. For that purpose, the TMI-2 reactor was selected using a postulated core degradation scenario, specified with simple initial and boundary conditions so that the influence of uncertainty of these conditions was minimized [1]. This exercise was the first benchmarking of severe accident codes promoted by NEA since almost 20 years.

The objective of this action was to do the benchmark on a well-defined plant and with prescribed boundary conditions, in order to avoid additional and unwanted sources of discrepancies between code predictions and to focus on the ability of the codes to predict core degradation. In addition to the comparison of the different results, sensitivity studies were also done. For that purpose, it was decided to perform a further calculation with the same core degradation parameters for all codes.

The following organizations have participated in the benchmark study: ENEA (using ASTEC V1.3), GRS (ATHLET-CD Mod 2.1A), IVS (ASTEC V1.3), NRC-SNL (MELCOR 1.8.6), University of Pisa (MELCOR 1.8.5), IRSN (ICARE/CATHARE V2.1), Seoul National University (MAAP 4.03), IKE (ATHLET-CD/MEWA).

In the following section, the proposed accident scenario and the definition of the boundary conditions are presented. After that, the set of physical parameters chosen for comparison of results is described, followed by the discussion of the results and their comparison. A short conclusion and an outlook to possible extensions of the work in the future are given at the end of this paper.

2. Scenario and parameters

2.1 Definition of the Alternative Scenario

For a prediction as accurate as possible of the TMI-2 transient, an essential point is the proper definition of boundary conditions and plant characteristics. Since some of these data are either unknown or difficult to estimate, extensive efforts have been required from code users in order to estimate them. In particular, the data for make-up and let-down flows were not recorded during the TMI-2 accident. To avoid such problems, a new benchmark exercise was proposed, based on an alternative scenario. The idea was to do the calculations on a well-defined plant similar to TMI-2 in order to avoid further, unnecessary origins of discrepancies between the results.

At first, the standard TMI-2 plant with the complete primary circuit (loops A and B) and a simplified secondary circuit is modelled. The initial plant state corresponds to the standard TMI-2 accident sequence. Then, the accident is initiated by a small break with a size of 0.001 m² located at 4 m along the hot leg A, followed by the stop of the main coolant pumps when the primary coolant inventory drops below 85 tons. The high pressure injection (HPI) operation with 30 kg/s per loop is delayed until 5000 sec after the stop of primary pumps. Another assumption is that no pilot operated relief valve failure and no let-down flow occur. This scenario leads to a significant degradation and core melting before the reflooding of the core. At last, the calculation is stopped a few thousand seconds after the HPI operation or as soon as the core is completely cooled down.

The initial core power is 2700 MW and thermal heat losses from primary system to containment are not taken into account. The make-up flow in primary system amount to 3.0 kg/s and the boundary conditions for secondary system are given by the regulation of steam generator pressures and water levels. In the core with an active length of 3.66 m, there are 177 fuel bundles of type 15x15 and 208 fuel rods per assembly. The UO_2 mass amounts to 93650 kg, the zircaloy mass to 23050 kg, and the AIC mass (Ag + In + Cd) to 2750 kg.

2.2 Choice of Physical Parameters to Compare

In order to compare the results, the appropriate choice of physical parameters is a crucial requirement for a benchmark study. For this purpose, the selection of a parameter set was made according to three criteria: the relevance for safety and/or severe accident management (i.e. primary pressure, hydrogen production), the monitoring of the reactor state (i.e. water inventory, mass of molten materials), and the significance for more detailed comparisons of models (i.e. break flow rate, mass of dissolved UO_2). In the benchmark study, many parameters were used to compare the results. We present some of them in the following section.

In order to claim that a set of results is in good agreement with another one, it is necessary to define subjective criteria reflecting the level of uncertainty that is acceptable for a specific physical parameter predicted by a code. The used parameters are selected by comparing with uncertainties obtained in previous benchmarks (previous TMI-2 benchmark [2], PHEBUS-FPT1 benchmark [3], and QUENCH-11 benchmark [4]). In addition, some further variables are chosen to judge the quality of agreement. In comparison to previous benchmarks most uncertainties could be reduced considerably, as it can be seen in Table 1.

3. Discussion of results

The comparison of the predictions of core degradation and reflooding was the main goal of the benchmark exercise. But the initial phase of any severe accident sequence is a purely thermal-hydraulic, transient phase which can last a significant time, depending on the scenario. The influence of that initial transient on the subsequent degradation is essential because it determines the time of core uncovery and heat-up. The steady state at the beginning is well predicted by all codes. Differences in the predicted values are not significant and can be considered as acceptable.

The whole sequence of the accident was divided into three phases: the initial thermal-hydraulic phase, the core degradation phase, and, finally, the reflooding phase. The first phase lasts up to the stop of main pumps at a point in time of about 5000 sec when the mass of water contained in the primary system is lower than 85 tons. Afterwards, the phase of core degradation is following. In this time, the

HPI was delayed until 5000 sec after the stop of primary pumps and then, the third phase starts with the refilling of the vessel.

3.1 Initial Thermal-hydraulic Phase

In the initial phase, the mass flow rate at the break and the heat transfer to the secondary circuit determine the further events of the accident sequence. In Fig. 1 we can observe a good agreement in the mass flow rates for most of the codes, five of the curves are even almost identical. Here, the discharge from the break can be divided in three parts: liquid discharge up to the reaching of saturated conditions at about 200 sec, two-phase discharge flow until about 4500 or 5000 sec when the main pumps are stopped, and steam discharge up to the start of the reflooding phase at about 10000 sec. However, the UPI-Melcor calculation shows a slightly different behaviour of the break mass flow rate during the two-phase discharge, which becomes constant after some time, instead of slowly decreasing like the other ones. This leads to an earlier reaching of the criterion for the stop of pumps. By contrast, the SNU-MAAP4 calculation predicts a slightly lower flow after the initial rapid depressurization, but also the latest time for pump stop.

As expected, the evolution of the primary mass predicted by all participants is very similar to the mass flow rate at the break, see Fig. 2. The heat transfers with secondary side, the behaviour of the steam generators, the core temperatures, and the pressurizer level show good agreement among almost all codes. A few significant discrepancies exist at the water levels in the core. The reason of this may be several differences in the modelling of heat transfer between coolant and assemblies, of pump behaviour or of fluid stratification in the primary circuit.

3.2 Core Degradation Phase

When the pumps stop, the mass flow rate at the break is significantly reduced due to phase separation, and the primary mass decreases more slowly (Fig. 1 and Fig. 2). Simultaneously, the heat transfer to the secondary side is strongly reduced and the evolution of the primary pressure becomes independent of the secondary pressure. A progressive dry-out with a resulting uncovery of the core occurs, followed by the increase of temperature of the rods and the oxidation of the claddings.

As a consequence of the pumps stop, water in the loops is drained down into the vessel, leading to an increase of water volume in the vessel. All codes predict this increase of the collapsed level, as Fig. 3 illustrates. Following this rapid variation of the level, a progressive decrease of the water level is predicted, corresponding to the dry-out and core uncovery. All the curves show a similar behaviour, in particular, all the results agree on the prediction of the core dry-out. Only in the time of beginning of core uncovery exist some differences.

All codes show a slow decrease of the mass flow rate at the break, from a value of approximately 10 kg/s to a rather stable value of approximately 4 kg/s before reflooding, see Fig. 1. Only SNU-MAAP4 drops to zero and remains to the end of the calculation. Besides that, the primary mass decreases in all calculations.
However, the evolution of core temperatures show several differences, see Fig. 4. The curves may be divided into three parts: heat-up before oxidation, oxidation runaway, and "late phase" heat-up following the first relocation of molten materials. For the heat-up phase before oxidation, the slope is very similar for all curves, except for the IVS-ASTEC and the ENEA-ASTEC calculations which predict a delayed but steep heat up. The main discrepancy is the time of beginning of heat-up which varies from 500 sec to 1800 sec after pump stop, with a variance of 40%. The delay between curves is partly a consequence of the delay of core uncovery. Another cause is probably the differences in the melt relocation models or cladding failure criteria which lead to a different velocity or time of

propagation of the "hot" oxidation front. For the oxidation run-away, we can observe a surprising agreement among several results which predict this effect between 7500 sec and 8000 sec. The increase of temperature due to temperature escalation is very comparable for most results. The maximum predicted temperature after escalation is approximately 2300 K, which is related to the cladding failure criteria.

The predicted rate of hydrogen generation is similar for most results (approximately 0.6 kg/s in average). Relating to the delays observed in the core temperature curves, the main differences are the times of maximum production, as Fig. 5 shows. However, the cladding failure and first melting relocation are predicted at approximately the same time for most codes, which is a direct consequence of the good agreement on the time of oxidation run-away.

In contrast to the hydrogen production, the evolution of the total mass of molten materials show some differences, see Fig. 6. In some calculations, the predicted molten mass increases simultaneously, which means that the energy brought by oxidation is directly converted into latent heat to melt the oxides. By contrast, in other calculations the molten mass increases smoothly, even a long time after the oxidation run-away, which indicates that the oxidation energy is "stored" in the core materials. One reason for that discrepancy is the choice of melting temperature of the oxides. If this temperature is far from the temperature reached after the end of the oxidation run-away, then the melting must occur later than the oxidation. But there is a rather good agreement on the final mass of molten materials, the maximum variation obtained is 35%. The predicted mass of molten metal has even only a variation of 16%, according to the good knowledge of melting temperatures of metals.

The predicted states of the core at the beginning of the oxidation run-away appear to be rather consistent. The temperature distributions are similar, the core is divided into a cold lower part and a hot upper part which is uncovered. However, some calculations predict the position of the maximum temperature at the top of the core and others predict it slightly below the top. The states of the core at the beginning of the melt relocation (not shown here) show larger differences and the location of the first damages or melting varies significantly from one calculation to the other. Addionally, a difference is also observed in the predicted level of the "cold" zone, which is covered with water. Differences in pressure drops or heat transfer coefficients and flow distribution are probably the main causes for these discrepancies. Thus, the states of the core predicted just before the reflooding show both a very different distribution of materials and a very different temperature field. Some calculations show a large empty area at the top of the core, resulting from the collapse or melting of fuel rods. Other calculations show standing rods at the top of the core and a more limited molten area in the center of the core. But almost all calculations predict a very compact region of accumulated materials at approximately 1 m elevation. This may be interpreted as a "crust" or "crucible" made of relocated materials.

3.3 Reflooding Phase

All codes predict a fast increase of the water level in the core and the core by-pass with approximately the same velocity. In some calculations, discontinuities in the increase of the water level are observed, but they are probably due to the numerical tracking of the water level. At the end of the calculation, most calculations indicate a stable water level in the core, but the ASTEC-ENEA calculation shows a surprising decrease of the water level. The stabilized level varies between 3 m and 4 m in the different calculations.

The average predicted pressure increase of about 50 bars is in agreement with the real TMI-2 scenario, in which the pressure increase after the restart of the pumps is also in the order of 50 bars. There, the increase was attributed to a strong generation of steam and a strong oxidation resulting in a lot of hydrogen. By contrast, in the calculations considerably less hydrogen is produced during reflooding, so that the increase of pressure originates mainly from the steam formation.

Most codes of the benchmark exercise predict a fast quenching of the core at all elevation. However, the ATHLET/CD-GRS calculation predicts the non coolability of the inner ring at the bottom of the core and both ASTEC-IVS and ICARE/CATHARE-IRSN predict the non coolability of the middle of the core. Because the issue of coolability is crucial for safety studies, the reasons for such non coolability should be investigated more thoroughly.

A few codes predict some hydrogen production during reflooding but it is quite limited. Although a few codes yield a finite hydrogen production, in most calculations the oxidation is predicted to stop as soon as the reflooding starts and no additional hydrogen is produced during reflooding. Those predictions do not agree with experimental findings as it was demonstrated by QUENCH program that the reflooding of a very hot but still undestroyed core should lead to a large hydrogen production. And the same observation was made during the TMI-2 accident where a considerable amount of the total hydrogen output was supposedly produced during reflooding. Recent studies suggest that hydrogen produced during reflooding mainly comes from the oxidation of melt containing Zr. Therefore, we may assume that there is an inadequate modelling of this phenomenon in current codes. This may also be a consequence of an inaccurate modelling of melt formation and relocation.

There is no significant increase of the degradation or core melting during reflooding. Hence, the predicted final state of core is very similar to the state before reflooding in almost all calculations. This result is contrary to observations in the QUENCH program in which it has been shown that the reflooding could lead to the melting of cladding and to a significant relocation of materials. But QUENCH tests are not fully representative of a core since there are no UO_2 pallets. Besides, the average predicted core temperature in this scenario is much higher than that in the QUENCH experiments. On account of this it is not possible to infer solely from experimental results that the code predictions are wrong.

3.4. Sensitivity Studies

Discrepancies between code results may have different origins. One of them observed in several previous benchmarks is the so-called “user effect”. User effect may result from an improper checking of the data or from a wrong use of the code by an insufficiently trained user. In order to avoid this effect, recommended values of the parameters used in the models are usually provided to code users in calculation benchmarks.

All the reference calculations of this benchmark were done with the recommended values of physical parameters. Therefore, it was decided to perform a second calculation with the same core degradation parameters for all codes in order to asses the discrepancies due to the user effect. For that purpose, aset of parameters known to have a significant impact on degradation calculations (like e.g. Zr oxidation correlation or melting temperature of oxides) were selected and given to participants.

Since standard core degradation parameters are somewhat different for each code, direct comparisons between sensitivity calculation results cannot be made. However, some conclusions can still be drawn. The variation of the melting temperature of oxides has a strong impact on the final mass of molten material causing a variation which is of the same order of magnitude as the variation obtained with different codes and/or users. This shows that the physical understanding of fuel rod melting and collapse is still too limited. The variation of cladding failure criteria also causes a variation which is comparable to the variation obtained with different codes and/or users. However, the impact of the variation of the selected parameters on the reflooding phase and on the final state of the core seems to be more limited.

4. Conclusions

This benchmark exercise has been the first exercise supported by the NEA, since the TMI-2 exercise which took place almost 20 years ago, to assess the ability of current codes to predict severe accidents in real reactors. In the framework of the benchmark, an "alternative" TMI-2 scenario with some fixed boundary conditions was defined, in order to minimize the uncertainties coming from the thermal-hydraulic calculation, and to focus the exercise on the uncertainties coming from the core degradation calculation.

For the initial thermal-hydraulics phase, up to pumps trip, the predicted results are in good agreement and most of the discrepancies can probably be explained by different modelling approaches. The states of the core and the primary circuit predicted by all codes are very similar at the time of pumps stop. For the degradation phase, up to reflooding, the results show a rather good agreement among all participants for the global parameters such as the total hydrogen production and the total mass of molten materials. These results are much better than in the benchmark exercise performed 20 years ago. For the reflooding phase, there is a general agreement on the predicted hydrogen production and the increase of degradation. However, although all codes agree, the results may be questionable as they are apparently in contradiction with some experimental results and with the TMI-2 assumed evolution. There is a disagreement between the predicted quenching efficiency. Although the abilities and robustness of codes have been considerably improved, compared to the previous TMI-2 benchmark exercise where almost none of the codes were able to calculate the reflood phase, it can be concluded that more effort on modelling and assessment should be done before codes can be considered as reliable enough to predict accurately the reflooding phase.

Altogether, the results of this exercise benchmark are quite encouraging. All codes used in this exercise succeeded in calculating the scenario from the beginning to the end, with only very little tuning of parameters or optimization of input decks. This demonstrates the robustness of current codes and is evidence of a great progress in comparison to the state of codes 20 years ago. It appears that the predictions of codes are significantly more consistent than in previous benchmarks.

Taking into account that, from a regulatory point of view, it is essential that uncertainties in best-estimate calculations be well studied and assessed, it is suggested that systematic uncertainty analysis be included in future extension of this benchmark, using uncertainty analysis techniques. The BEMUSE program action, which is being carried out in the frame of GAMA, could be a good reference for that. This benchmark exercise could also be extended to study the consequences of severe accident management (SAM) actions and how such actions can be simulated by current codes.

References

1. *Ability of Current Advanced Codes to Predict Core Degradation, Melt Progression and Reflooding - Benchmark Exercise on an Alternative TMI-2 Accident Scenario* NEA/CSNI/R(2009)3 (2009)
2. *TMI-2 Analysis Exercise Final Report*, NEA/CSNI/R(91)8 (1991)
3. *ISP-46 PHEBUS FPT1*, NEA/CSNI/R(2004)18 (2004)
4. *SARNET Benchmark on Quench-11 – Final Report*, FZKA 7368 – SARNET CORIUM P008 (2008)

Table 1. Uncertainties of benchmark variables

Variables	Current benchmark	Previous benchmarks
Time of pump stop	+/- 3 %	specified
Minimum steam generator pressure	+/- 11 %	NA
Maximum steam generator level	+/- 11 %	NA
Primary pressure before reflooding	+/- 14 %	> 30% TMI2
Loop flow rate before pump stop	+/- 40 %	NA
Loop flow rate during core reflood		> 200% Q11
Pump A void fraction (at pump stop)	+/- 10 %	NA
Maximum core temperature	+/- 300K ~11 %	+/- 350K TMI2 +/- 150K FPT1 +/- 500K Q11
Maximum hot leg temperature	+/- 10 %	NA
Break flow rate	+/- 30 %	NA
Total primary mass at pump stop	+/- 28 %	+/- 50% Q11
Swollen water level in the core (before HPI operation)	+/- 10 %	NA
Collapsed water level in the core		NA
Time of oxidation runaway	+/- 42 %	17% TMI2
Cumulated hydrogen production	+/- 18 %	+/- 33% TMI2 +/- 10% FPT1 +/- 20% Q11
Power exchanged with SG		NA
Max. instantaneous hydrogen production	+/- 30 %	NA
Total mass of molten materials	+/- 35 %	+/- 67% FPT1 +/- 100% Q11
Total mass of molten metals	+/- 16 %	NA
Total mass of dissolved UO_2	+/- 80 %	NA
Fraction of non-oxidized Zr in the molten materials	+/- 100 %	NA
Fraction of non-oxidized Zr (total)	+/- 10 %	NA

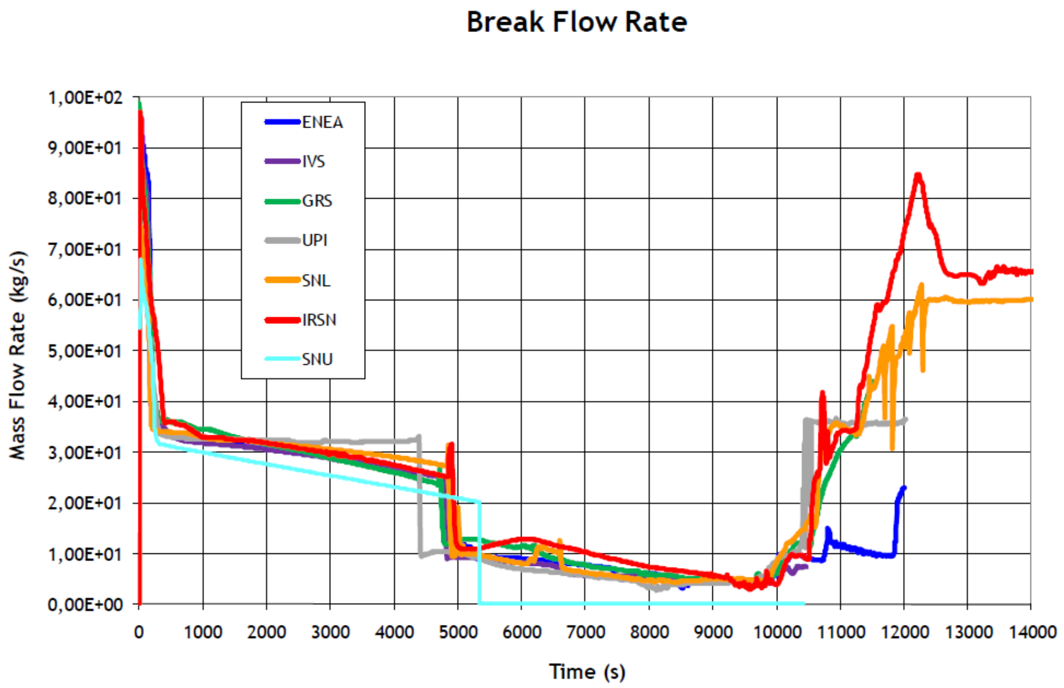

Fig. 1 Break Flow Rate

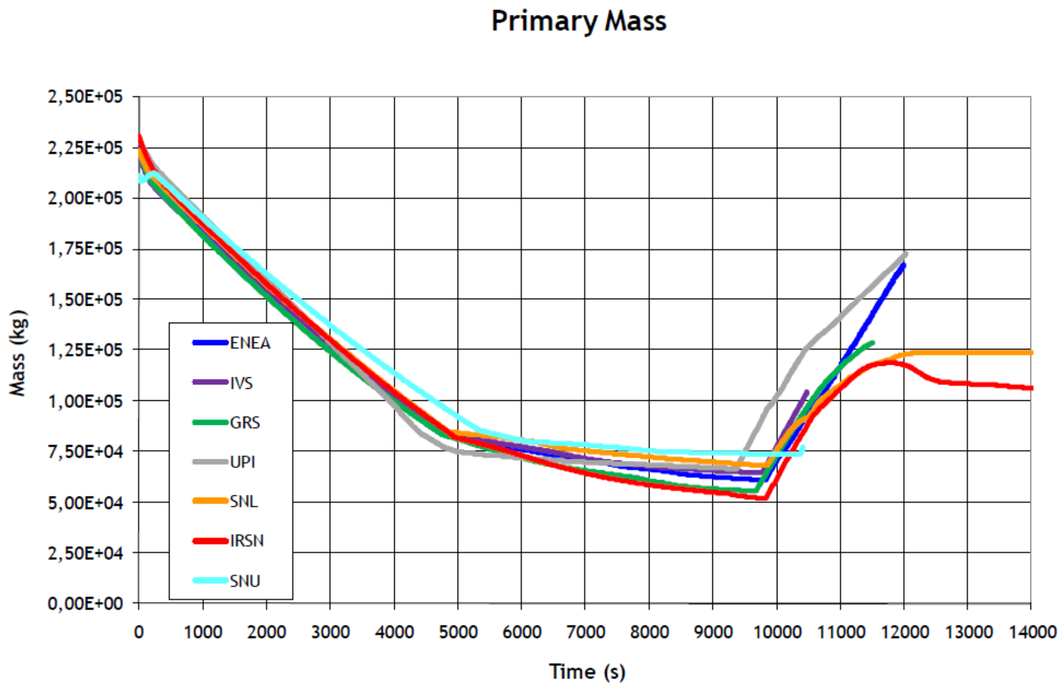

Fig. 2 Primary Mass

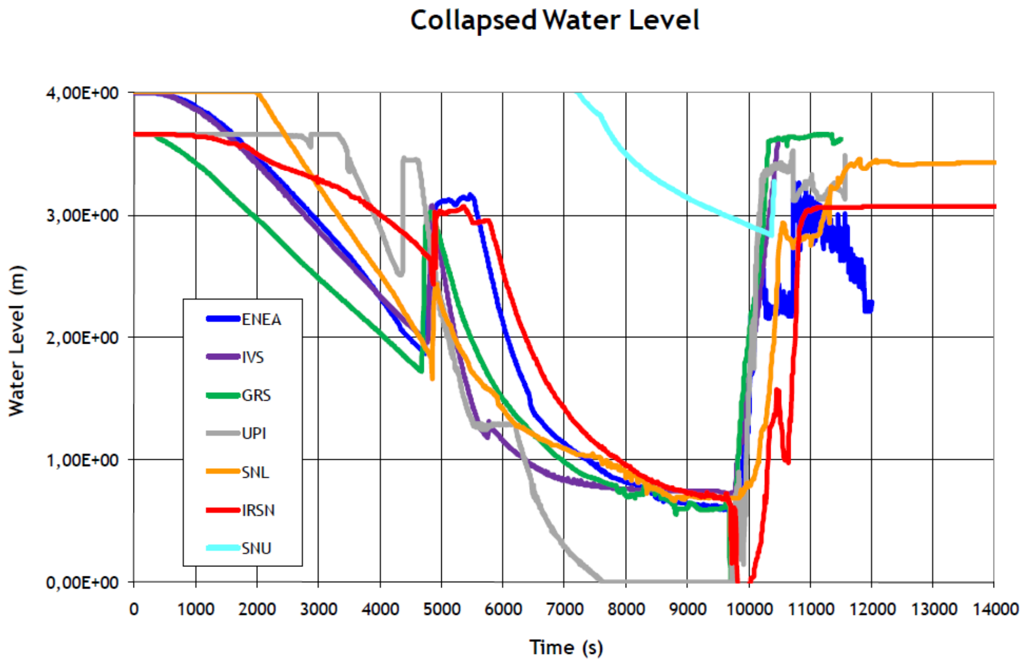

Fig. 3 Collapsed Water Level

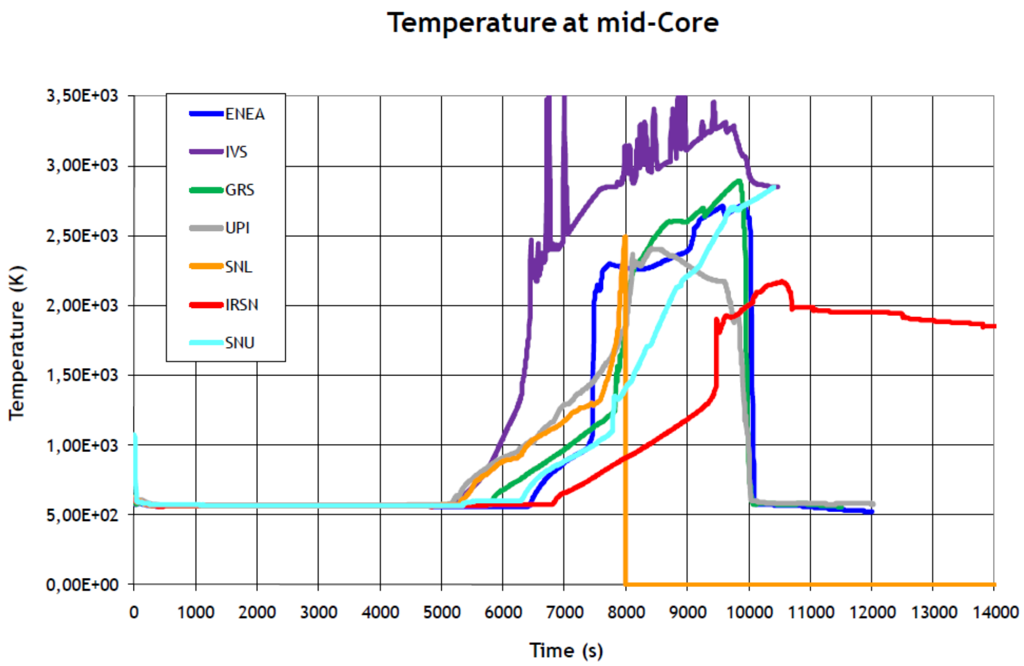

Fig. 4 Temperature at mid-Core

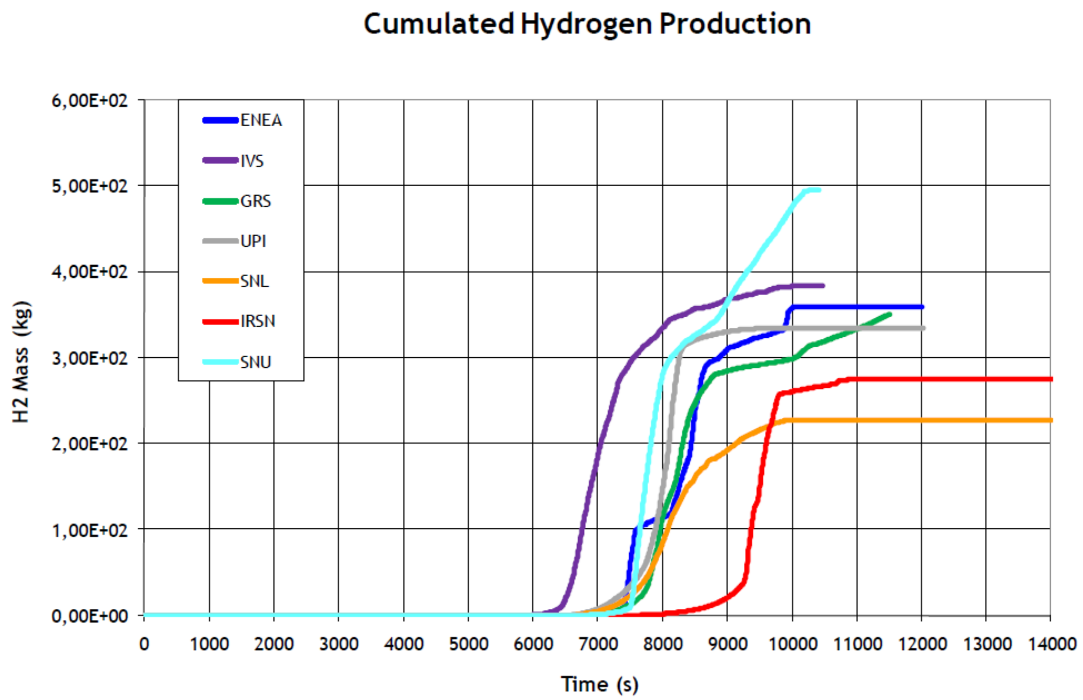

Fig. 5 Cumulated Hydrogen Production

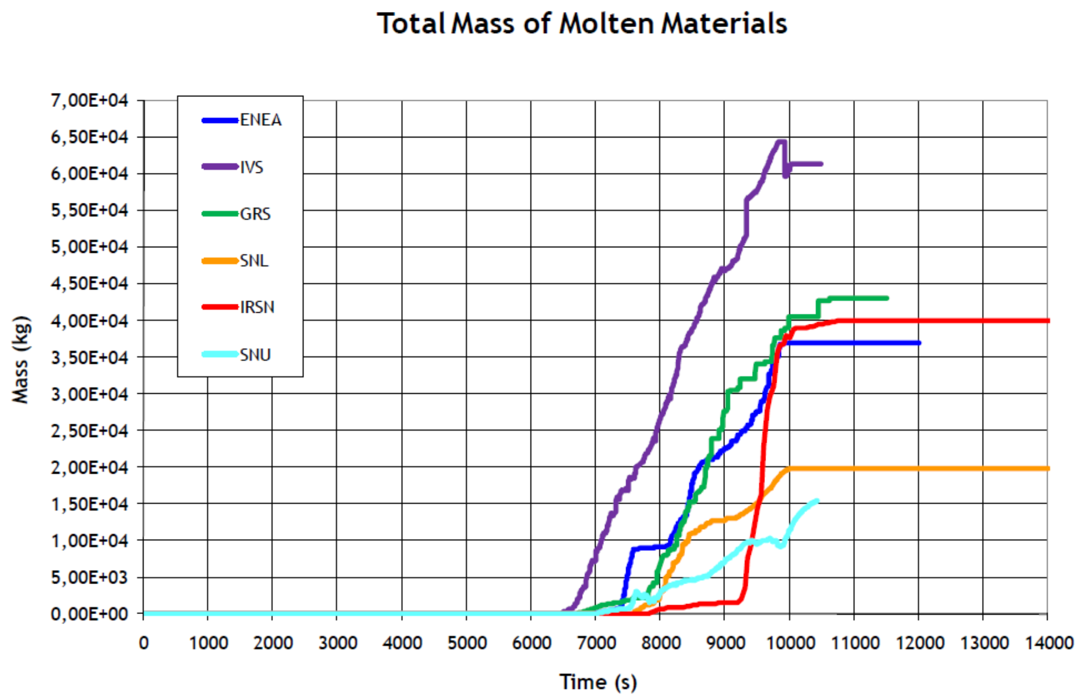

Fig. 6 Total Mass of Molten Materials

A Benchmark Exercise on an Alternative TMI-2 Accident Scenario

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Workshop on In-Vessel Coolability

October 12-14, 2009, Issy-les-Moulineaux

Outline

- Motivation
- Participants and Codes
- Definition of the Alternative Scenario
- Results
- Conclusions and Outlook

GRS

Motivation

- uncertainty by using different initial and boundary conditions in previous benchmark exercises
- a benchmark action has been launched by OECD/NEA GAMA in order to determine the ability of current codes to predict core degradations in nuclear reactors
- selection of the TMI-2 reactor using an alternative scenario with simplified initial and boundary conditions in order to minimize the influence of uncertainty of these conditions
- in addition: sensitivity studies with same core degradation parameters for all codes

GRS

Participants and Codes

ENEA	ASTEC V1.3
IVS	ASTEC V1.3
University of Pisa	MELCOR 1.8.5
IKE	ATHLETH-CD / WABE / MEWA
IRSN	ICARE/CATHARE V2
US NRC / Sandia NL	MELCOR 1.8.6
Soul National University	MAAP 4.03
GRS	ATHLET-CD 2.1A

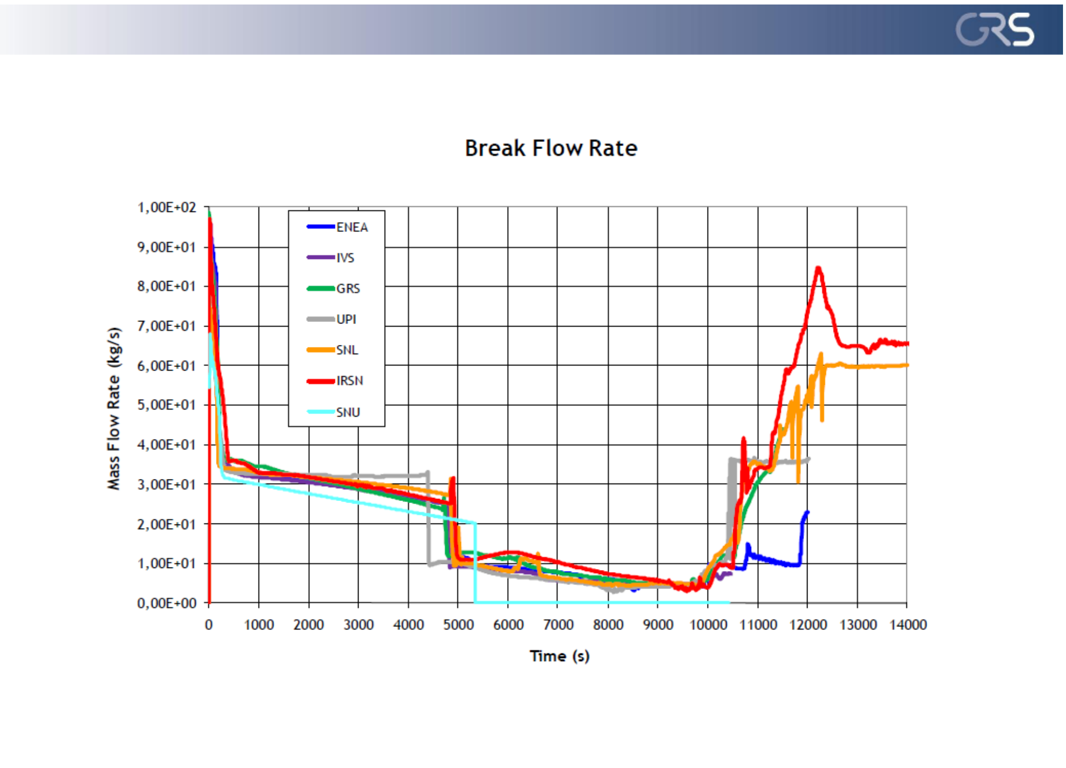
Definition of the Alternative Scenario

Calculations based on a well-defined plant scenario similar to TMI-2 in order to avoid unnecessary sources of discrepancies:

- complete primary circuit (loops A and B), simplified secondary circuit
- initial plant state corresponding to standard TMI-2 accident sequence
- small break with a size of 0.001 m² located at 4m along the hot leg A
- HPI operation delayed until 5000 sec after stop of main pumps
- no pilot operated relief valve failure, no let-down flow
- stop of the calculation a few thousand seconds after HPI operation or as soon as the core is completely cooled down

Results

- main goals: comparison of core degradation and reflooding
- good prediction of the steady state by all codes
- three phases:
    1) initial thermal-hydraulic phase (until stop of main pumps)
    2) core degradation phase (until reflooding)
    3) reflooding phase (until a few thousand seconds after the HPI operation or until the core is completely cooled down)



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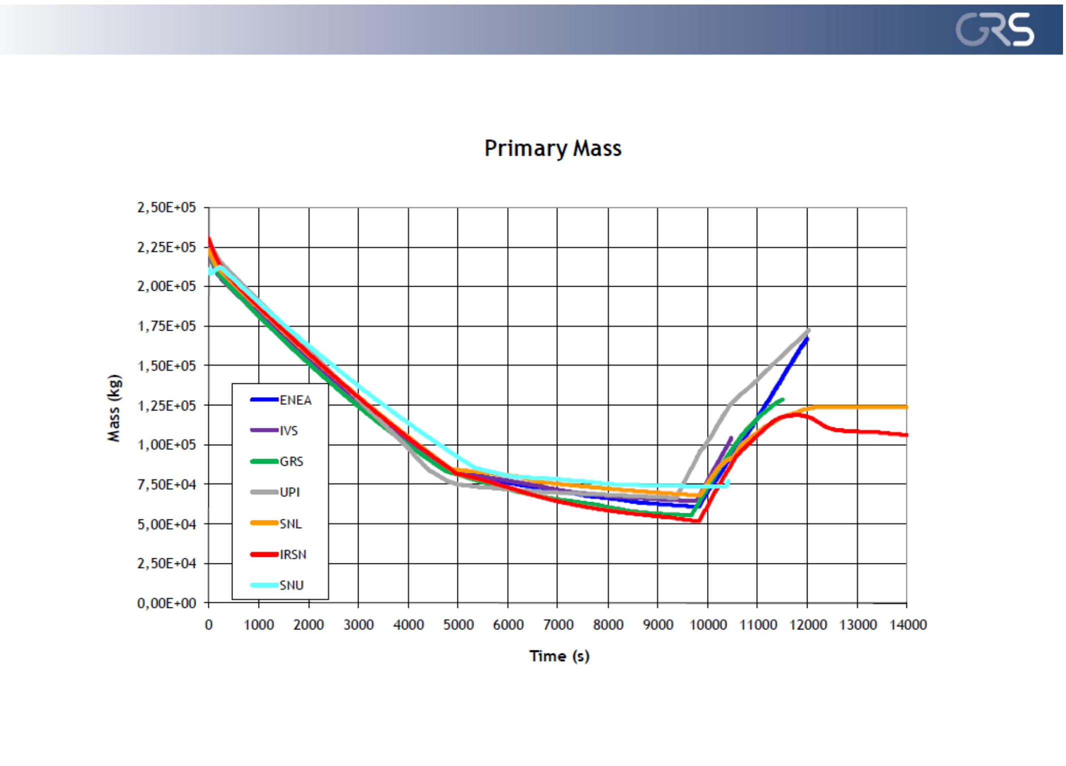

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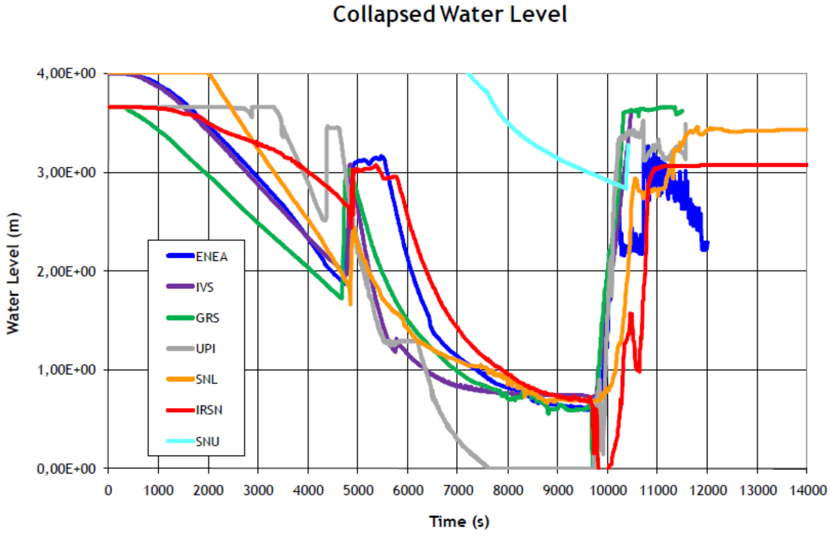

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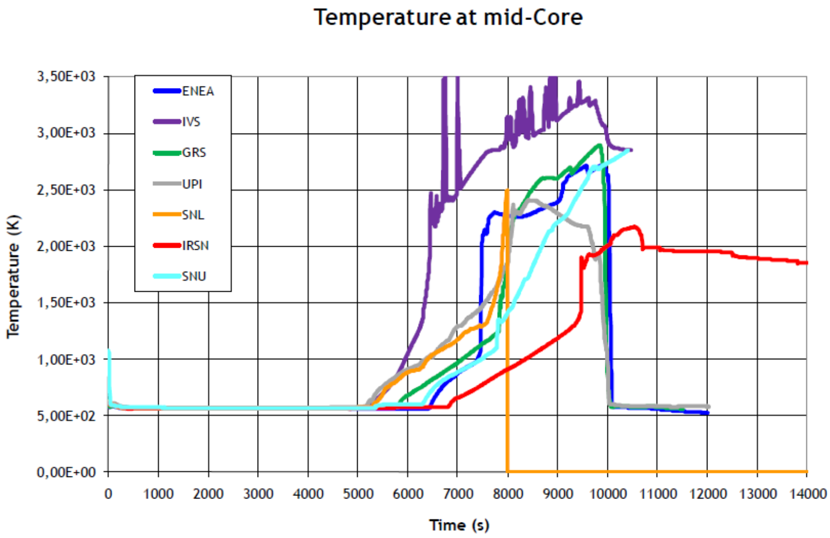

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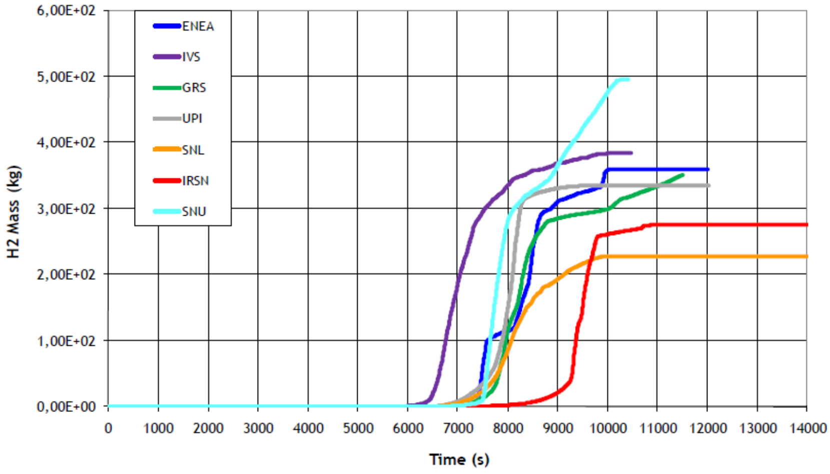
Cumulated Hydrogen Production



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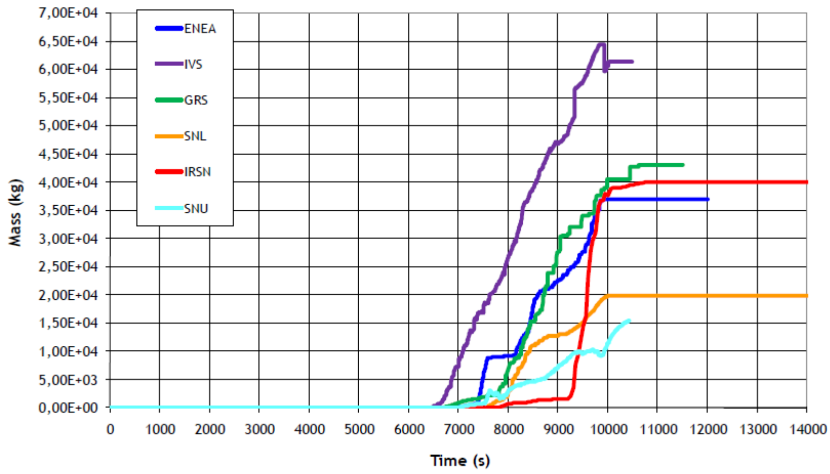
Total Mass of Molten Materials



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Initial Thermal-hydraulic Phase

- first phase is governed by mass flow rate at the break and heat transfer to the secondary circuit
- mass flow rate: good agreement for most of the codes
- very similar evolution of primary mass
- a few significant discrepancies in the water levels in the core, possible reasons: several differences in the modelling of the heat transfer, pump behaviour or fluid stratification in the primary circuit

Core Degradation Phase

- after stop of pumps: reduced mass flow rate at the break
- temporary increase of the collapsed level due to draining down of the water into the vessel
- this phase is characterized by a progressive dry-out and uncovery of the core, followed by the increase of temperature of the rods and the oxidation of the claddings
- several differences in the evolution of core, e.g. the time of beginning of heat-up due to the delay of core uncovery and some differences in the melt relocation models

Core Degradation Phase

- similar results in the rate of hydrogen generation, some differences in the times of maximum production
- differences in the evolution of the total mass of molten materials, but rather good agreement on the final mass of molten materials
- good agreement on the states of the core at the beginning of the oxidation run-away, main difference: the position of the maximum temperature (top or slightly below the top)
- prediction of a very compact region of accumulated materials at approximately 1 m elevation by almost all calculations

Reflooding Phase

- all codes: fast increase of the water level in the core with approximately the same velocity
- fast quenching of the core at all elevation in most codes
- non coolability of zones in the calculations of ATHLET/CD-GRS, ASTEC-IVS and ICARE/CATHARE-IRSN

  ➡ further investigations of the reasons for such non coolability
- no significant increase of the degradation or core melting
- only limited hydrogen production during reflooding

Conclusions and Outlook

- first benchmark exercise supported by the NEA since 20 years
- use of an alternative TMI-2 scenario with some fixed boundary conditions
- all codes succeeded in calculating the scenario from the beginning to the end
- good agreement among all participants in the first and second phase
- a general agreement on the predicted hydrogen production and the increase of degradation in the third phase, but contradiction with some experimental findings
- with respect to the third phase, more effort on modelling and assessment should be done
- this benchmark exercise could be extended to study the consequences of severe accident management (SAM) actions