NURETH-15 – 544

Progress on Severe Accident Code Benchmarking in the Current OECD TMI-2 Exercise

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15th International Topical Meeting
on Nuclear Reactor Thermalhydraulics, NURETH-15
Pisa, Italy, May 12-17, 2013

Outline

- Introduction
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- Participants and Codes
- SBLOCA Transient Result Comparison
- Results from Reflooding Sequences
- Conclusions

Introduction

- Based on the conclusions of a previous benchmark exercise on an alternative TMI-2 scenario (ATMI), the Working Group on the Analysis and Management of Accidents (WGAMA) of OECD/NEA felt it worthwhile to extend the accident analysis scope by examining the capability of the codes to predict core melt progression and the effects of severe accident management (SAM) actions under a variety of severe accident situations in order to challenge them to the full extent of their capabilities, recognizing, however, that they are less reliable in predicting late phase core melt progression
- As the activity of the SARNET-2 (WP5) project of EU FP7 was focused on late phase phenomena and debris coolability, WGAMA and SARNET-2 WP5 jointly proposed a benchmark as a follow-up to the ATMI benchmark exercise and which includes late phase core degradation, during different severe accident sequences, and core reflooding scenarios
- The proposal was approved by the OECD/NEA Committee on the Safety of Nuclear Installations (CSNI) in December 2010

Objectives

- The objective of the new Benchmark Exercise on TMI-2 plant is to gather information on the capability of codes/models to predict the key phenomena during reactor severe accident by comparing the various results from several computer codes
- The proposed directions are:
  - To simulate three representative severe accident sequences with well defined boundary conditions up to different degree of in-vessel core melt progression:
    - Two of the sequences will address core reflooding issue starting from different degree of core degradation
    - One sequence will extend to molten core slumping into the lower plenum
  - To perform some sensitivity studies on more important and uncertain key parameters in order to evaluate their impact on core degradation, core coolability and hydrogen production
  - To extend the number of participants in order to involve more countries, more users and young engineers

Participants and Codes

Participant	Country	Code
GRS	Germany	ATHLET-CD
IKE		ATHLET-CD
KIT		ASTEC & MELCOR
RUB		ATHLET-CD
ENEA	Italy	ASTEC
IRSN	France	ICARE/CATHARE
IVS	Slovak Republic	ASTEC
Tractebel Engineering	Belgium	MELCOR
BARC	India	ASTEC
IBRAE RAS	Russia	SOCRAT
INRNE	Bulgaria	ASTEC

11 Organizations

8 Countries

5 Codes

12 Calculations:

- **ASTEC (5)**
- **ATHLET-CD (3)**
- **MELCOR (2)**
- **ICARE/CATHARE (1)**
- **SOCRAT (1)**

- **This project is linked with the WP5.4 "Corium and Debris Coolability – Bringing Research into Reactor Applications" of EU/SARNET-2 network of excellence**
- **The activity is carried out by a Group of Participants including members from WGAMA and SARNET-2**

SBLOCA Accident Sequence

- **INITIAL EVENT:** small break of 20 cm^2 in the hot leg of Loop A, with contemporary loss of SG main feedwater
- Reactor scram on high pressure signal
- Auxiliary feedwater startup after 100 s
- Primary pump coastdown when primary mass inventory < 85 tons
- No HPI or LPI system actuation
- **Free evolution of the transient until vessel failure**

BOUNDARY CONDITIONS:

- Pressure and level control on SG secondary side:
  - *Constant value of steam pressure = 70 bar after 200 s*
  - *Constant value of water level = 1 m after t = 200 s by auxiliary feedwater injection*
- No letdown
- Constant value of make-up flow rate = 3 kg/s over the whole transient

Core Degradation Parameters

Participant	Zircaloy oxidation kinetics	Cladding failure criteria (e = oxide layer thickness)	Melting temperature of UO_2-ZrO_2	Debris formation criteria	Debris porosity and particle diameter
GRS (ATHLET)	Cathcart + Urbanic	T > 2300 K and e < 0.3 mm or T > 2500 K	2600 K	2400 K	38% and 2 mm
ENEA (ASTEC)	Cathcart + Prater	T > 2300 K and e < 0.3 mm or T > 2500 K	2550 K	2500 K	40% and 3 mm
IRSN (ICA/CAT)	Cathcart + Prater	T > 2300 K and e < 0.3 mm	2550 K	2500 K	30% and 3 mm
RUB (ATHLET)	Cathcart + Urbanic	T > 2300 K and e < 0.3 mm or T > 2500 K	2600 K	No debris bed modelling	-
IVS (ASTEC)	Urbanic	T > 2260-2450 K and e < 0.16-0.3 mm or T > 2500 K	2830 - 2873 K	2260-2500 K	30% and 9 mm
KIT (ASTEC)	Cathcart + Prater	T > 2300 K and e < 0.3 mm or T > 2500 K	2550 K	No debris bed modelling	-
IBRAE-RAS (SOCRAT)	Diffusion	T > 2300 K and e < 0.3 mm or T > 2500 K	UO2: 2850 K ZrO2: 2900 K U-Zr-O: 2250-2850 K	No debris bed modelling	-
BARC (ASTEC)	Cathcart + Urbanic	T > 2300 K and e < 0.3 mm	2600 K	2600 K	60% and 3 mm
Tractebel (MELCOR)	Urbanic	T > 2400 K and e > 0.01 mm or T > 3100 K	2800 K	2400-3100 K	40% and 2 mm
IKE (ATHLET)	Cathcart + Urbanic	T > 2300 K and e < 0.3 mm or T > 2500 K	2600 K	No debris bed modelling	-
INRNE (ASTEC)	Urbanic	T > 2600 K and e < 0.25 mm or T > 2700 K	2750 K	2800 K	40% and 2 mm

Core degradation parameters

The value of the different parameters has been selected according to code best practice guidelines and user experience

Sensitivity studies have been performed and are in progress to investigate the influence of different parameters on core melt progression and hydrogen generation

Main Steady-State Plant Parameters

Parameter	Unit	Calculated values (range)	TMI-2 plant data
Reactor core power	MW	2772	2772
Pressurizer pressure	MPa	14.82 - 15.15	14.96
Hot leg temperature	K	589.3 - 594.8	591.15
Cold leg temperature	K	560.3 - 565.7	564.15
Primary loop flow rate	kg/s	8472 - 8888	8800
Pressurizer collapsed level	m	5.05 - 5.94	5.588
Total primary mass	kg	219830 - 225650	222808
SG secondary pressure	MPa	6.41 - 6.55	6.41
SG steam temperature	K	564.7 - 588.3	572.15
SG feed water flow rate	kg/s	701.8 - 791.0	761.1

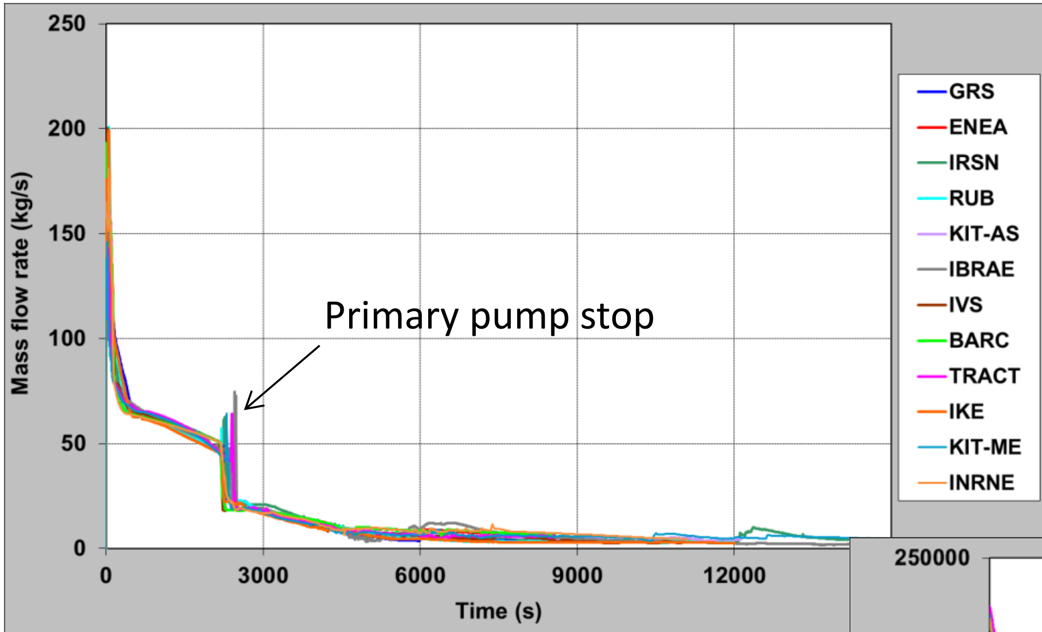
- **The variation range of primary system parameters is rather small**
- **Larger deviations are observed in secondary side parameters, but their influence on the transient behaviour was not significant**

Chronology of main events

Parameter	Unit	Calculated time values (range)
Break opening and loss of SG feed water	s	0
Stop of primary pumps	s	2089 - 2320
First fuel rod clad perforation/burst	s	3642 - 4488
First clad melting and dislocation	s	3806 - 4921
First ceramic melting and dislocation	s	4246 - 5203
First molten material slumping in lower plenum (core slumping not modelled by RUB and IKE)	s	4240 - 7633
Vessel failure (not predicted in IRSN, IVS and IBRAE RAS calculations)	s	8560 - 15980

- **The spreading in vessel failure timing is influenced by the vessel failure mode (creep, wall melting, penetration failure) and the assumption taken on molten jet break-up during slumping with formation of more or less coolable debris bed into the lower head of the vessel**

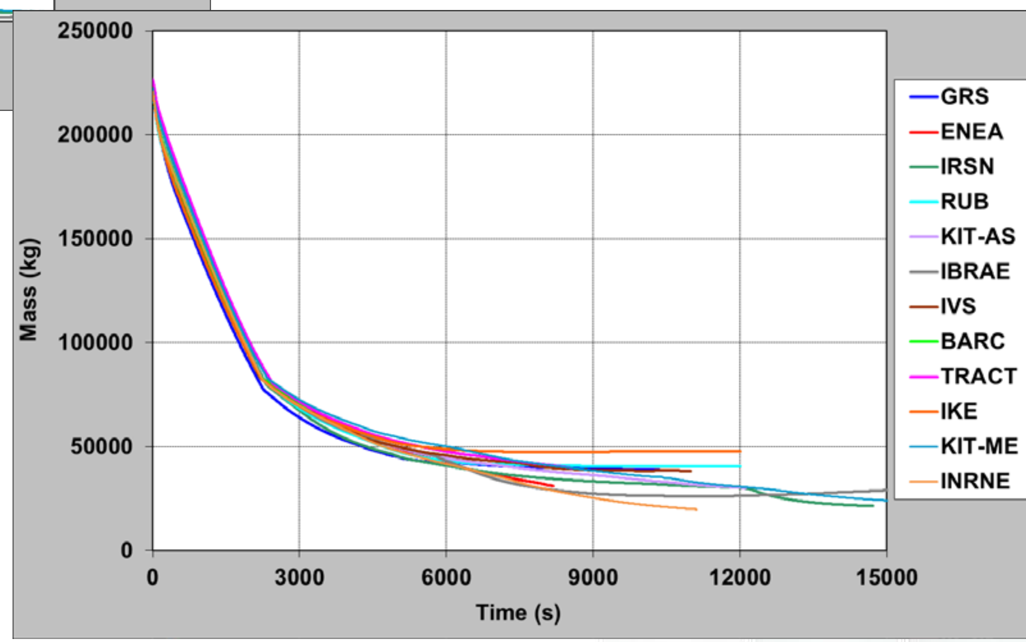
Code-to-code Result Comparison (1/4)



Break Mass Flow Rate

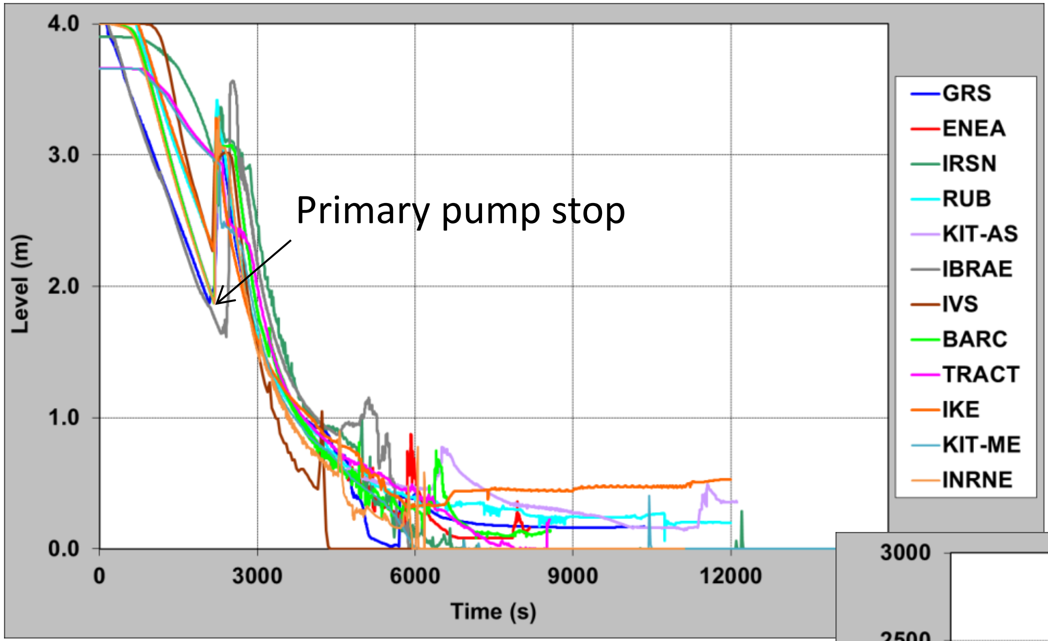
- No significant deviations in break flow rate evolution in all phases of the transient → rather good agreement in the primary mass inventory decrease

Total Primary Coolant Mass



- The timing of primary pump stop (primary mass < 85 tons) is almost coincident in all calculations
- Calculation are stopped after vessel failure

Code-to-code Result Comparison (2/4)

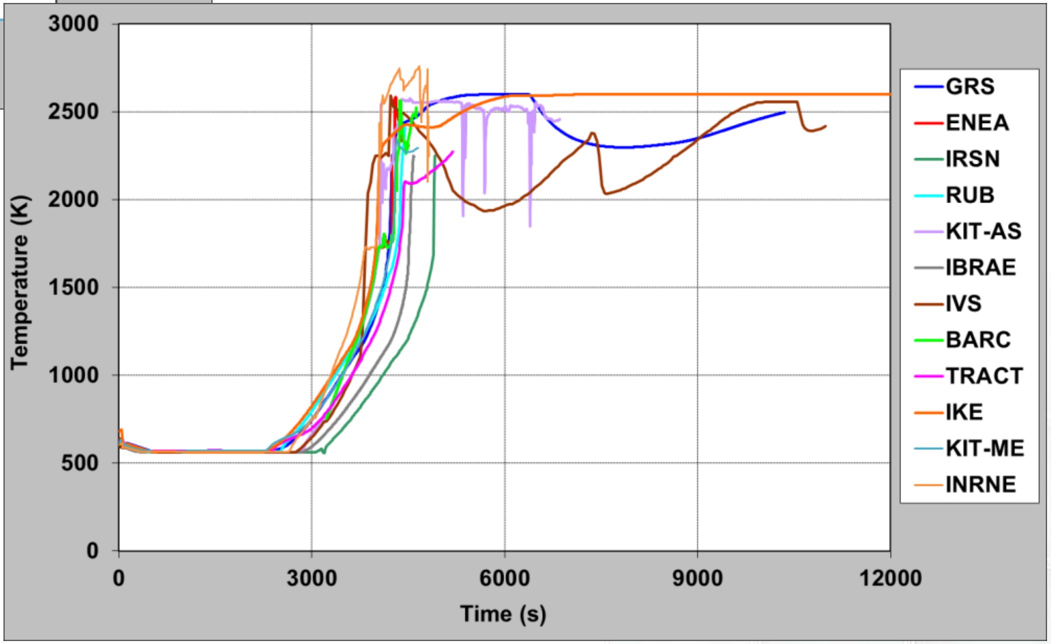


Core Collapsed Water Level

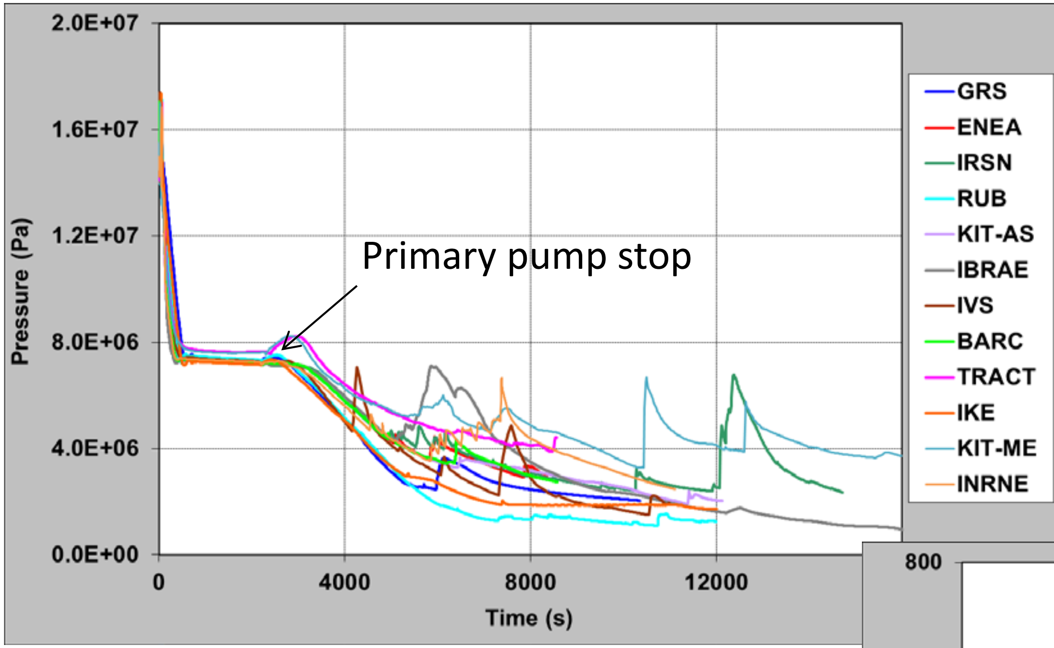
- Quite good agreement in initial core uncovery and heatup
- Larger deviations during the core degradation and core slumping phase

- Onset of core heat up is much delayed with ICARE/CATHARE, likely due to in vessel 3D T-H
- Stop of T-clad plotting means no material at the top due to relocation or debris bed collapse

Fuel Rod Clad Temp. at Core Top



Code-to-code Result Comparison (3 / 4)



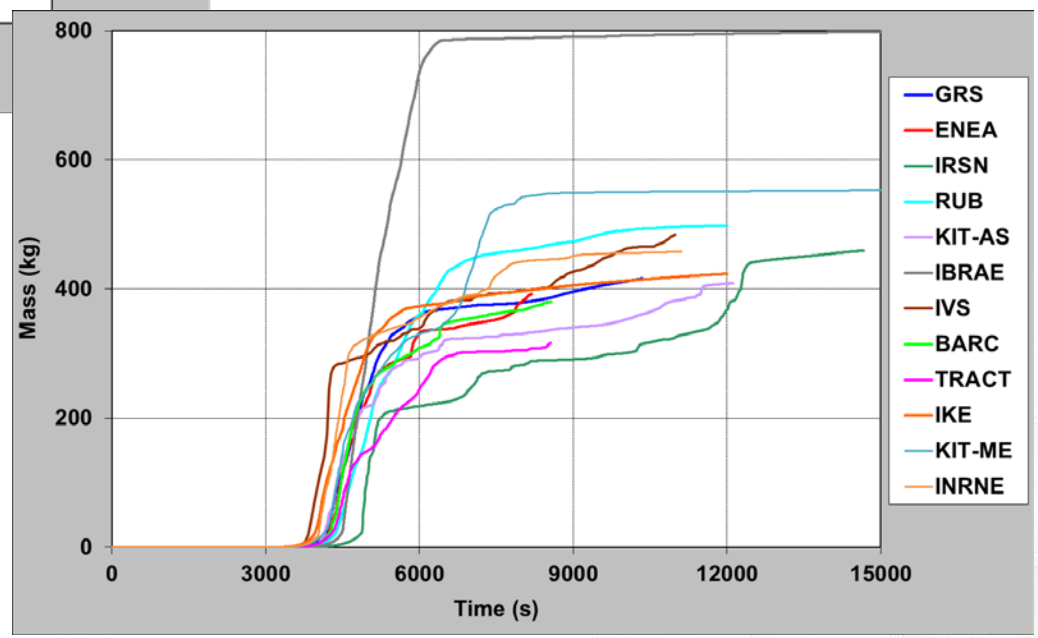
Pressurizer Pressure

- **Largest deviations in primary pressure behaviour are due to molten jet/water interaction during slumping leading to enhanced pressure peaks**

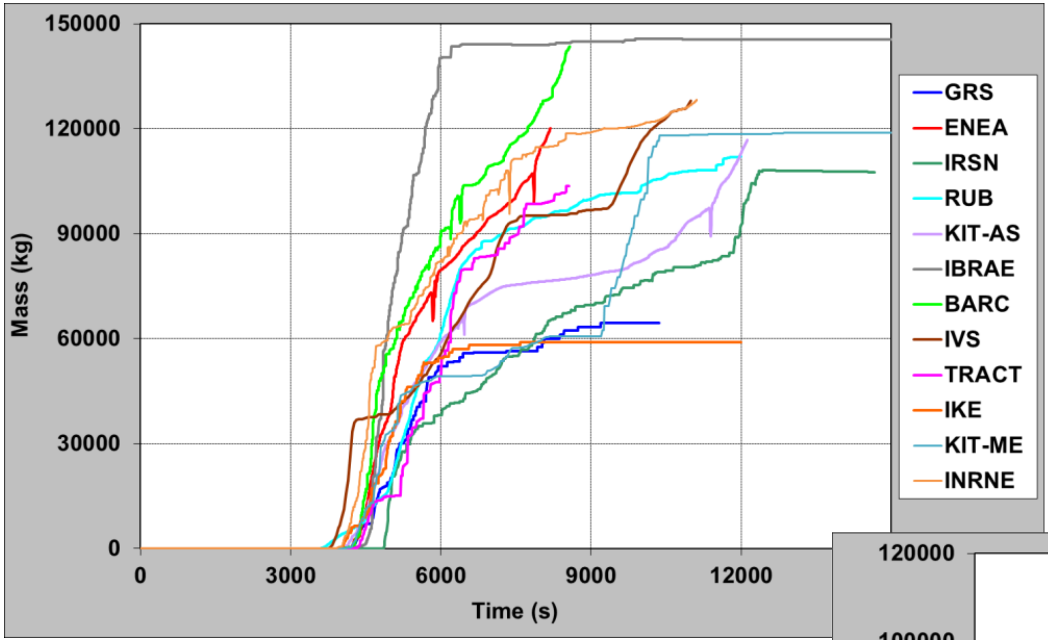
- **Most of the codes predict the H2 mass production in the range 400 – 500 kg. Only SOCRAT predicts up to 800 kg (oxygen diffusion kinetics)**

- **Different oxidation models and correlations**

Cumulated Hydrogen Production



Code-to-code Result Comparison (4/4)

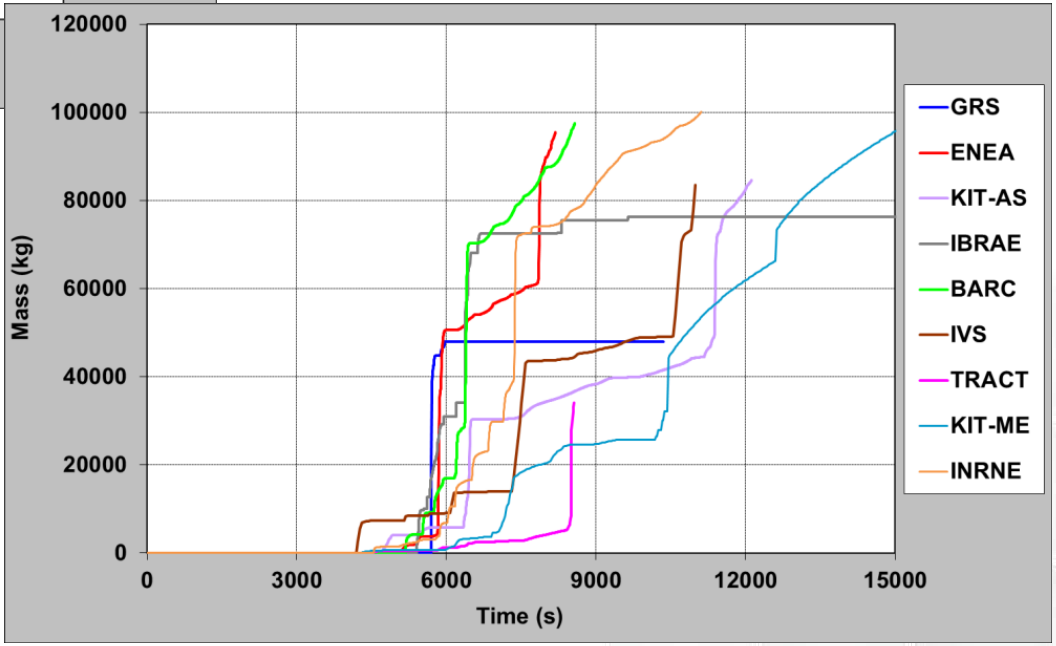


Mass of Degraded Core Materials

- Rather good agreement in onset of core degradation
- For most of the calculations the total mass of degraded core materials is around 120 tons

- Quite large spreading in the timing of molten core massive slumping in the lower plenum
- Relocation flow path is mainly through the core by-pass after baffle failure or melting

Mass Relocated in Lower Plenum

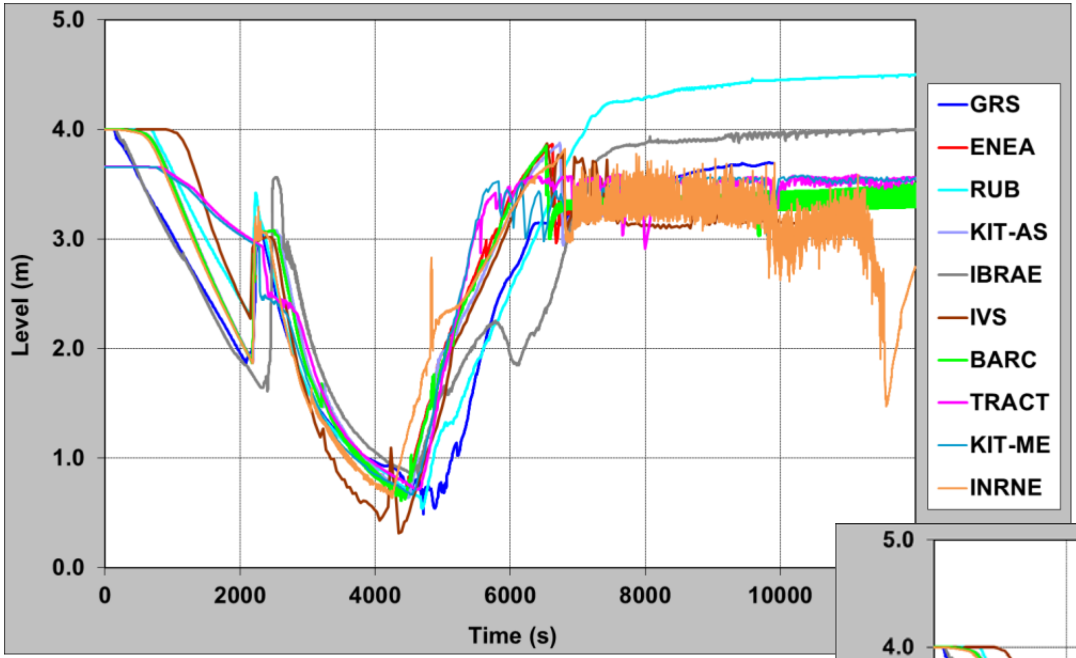


Reflooding Scenarios (SBLOCA sequence)

- For the SBLOCA scenario two reflooding sequences have been investigated starting from different core degradation conditions → Onset of HPI injection when:
  - 1st sequence: total mass of degraded core materials = 10 tons
  - 2nd sequence: total mass of degraded core materials = 45 tons
- Total water injection rate (HPI + make-up) = 28 kg/s (0.8 g/s per rod)
- From experimental evidence (QUENCH tests) the rate of 1 g/s per rod might be enough to cool-down the core and stop the melt progression
- Conditions at the limit of degraded core coolability are investigated since they seem the most challenging for the severe accident codes
- The calculations were stopped after the attainment of stable conditions or eventual vessel failure

Reflooding Sequence Results (1 / 7)

Core Collapsed Water Level

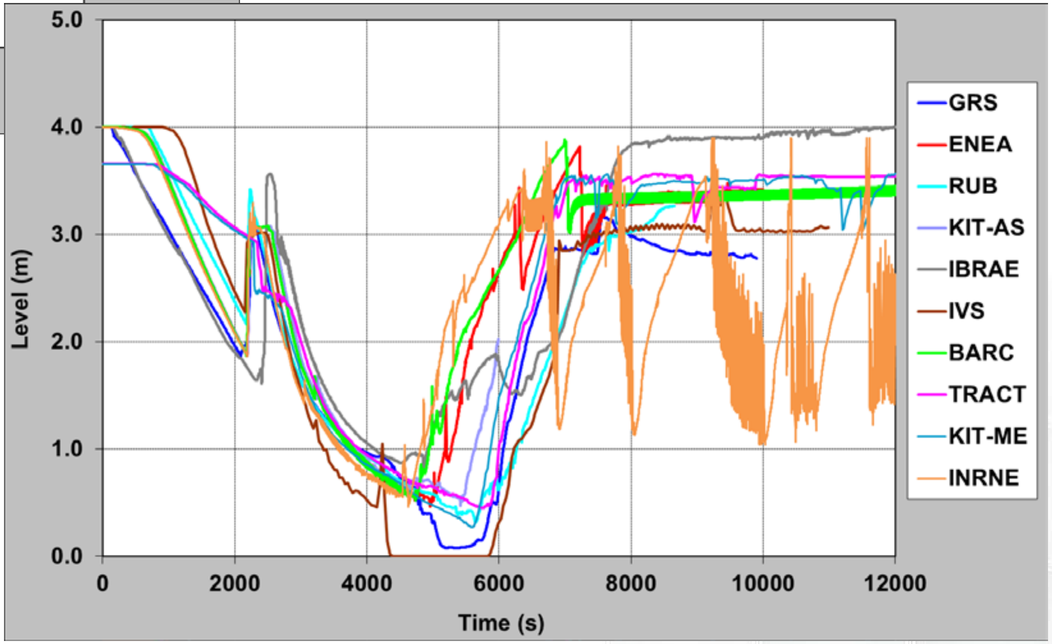


Degraded core mass = 10 tons

- **M = 10 tons:**
  general good agreement in onset of reflooding and core water level increase

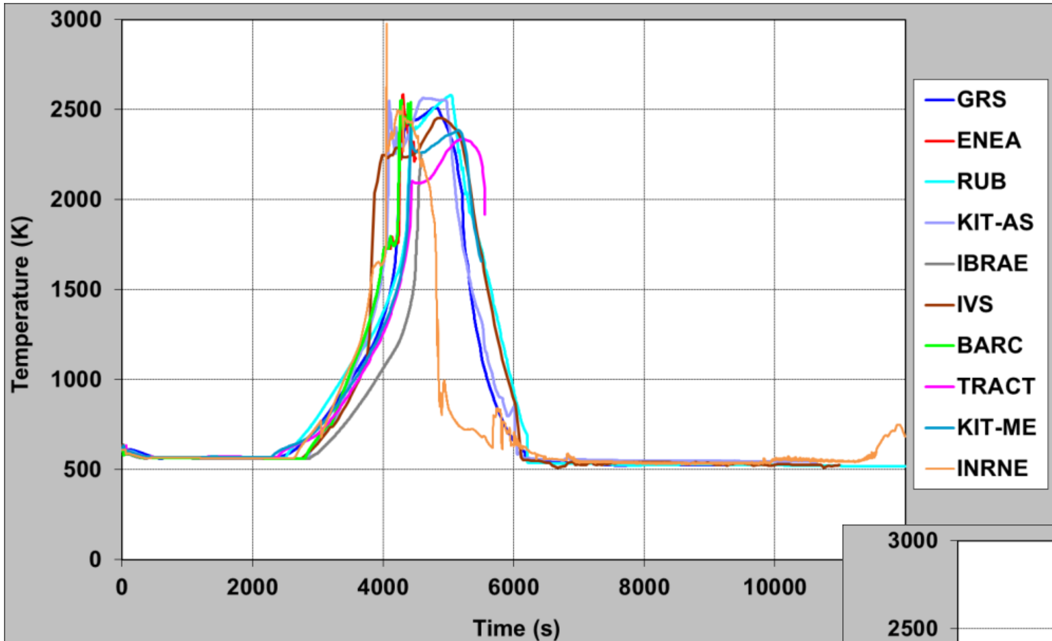
- **M = 45 tons:**
  general good agreement in water level increase but larger spreading in the onset of core reflooding

Degraded core mass = 45 tons



Refloodinq Sequence Results (2 / 7)

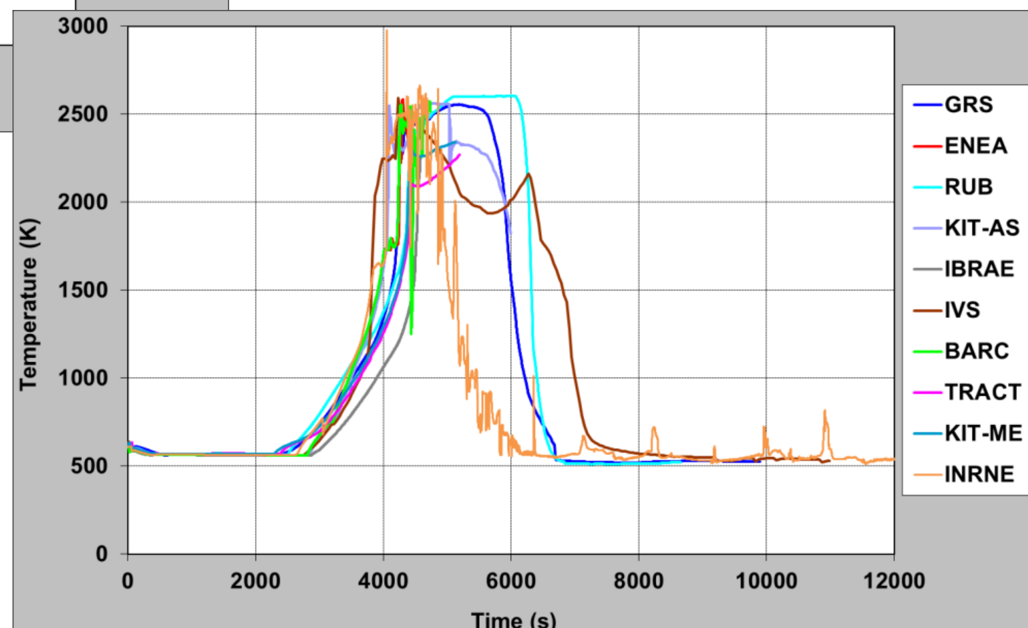
Fuel Rod Clad Temperature at Core Top



Degraded core mass = 10 tons

- Rather good agreement in cool-down rate at core top when fuel rods are still in place during reflooding

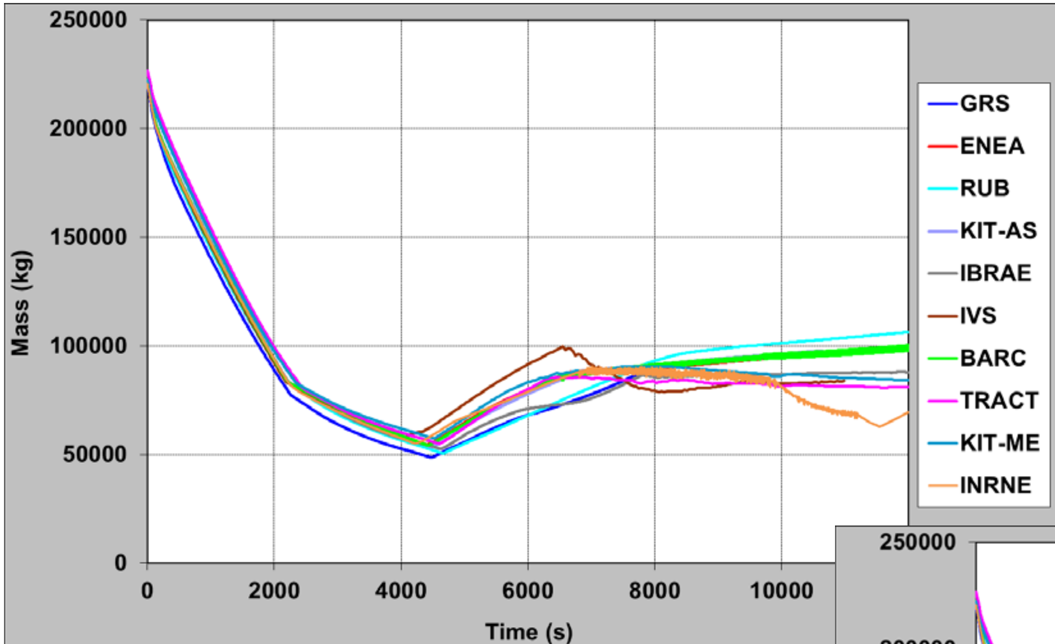
Degraded core mass = 45 tons



- Clad failure and relocation at core top cannot be prevented in most of the code calculations by the late core top reflooding

Reflooding Sequence Results (3 / 7)

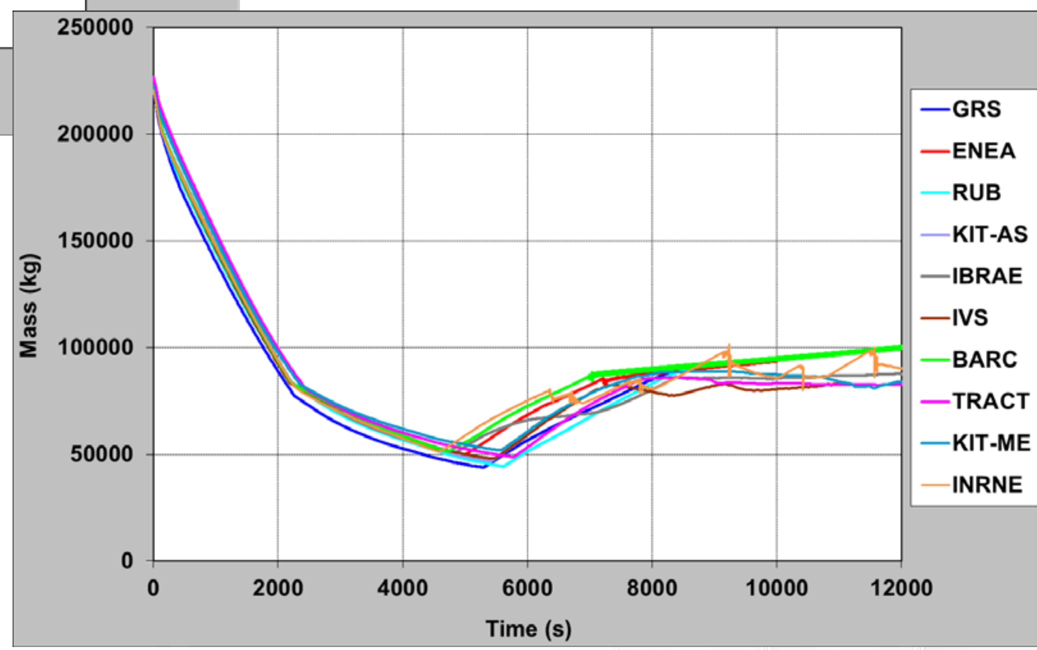
Total Primary Coolant Mass



Degraded core mass = 10 tons

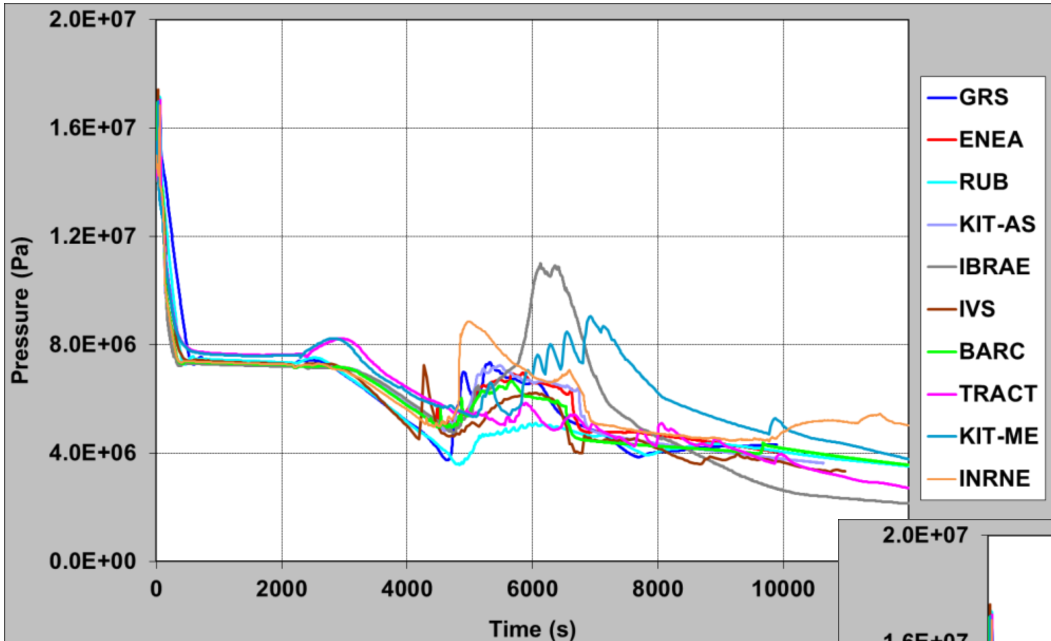
- **Rather good agreement in primary mass inventory at the end of the reflooding phase**

Degraded core mass = 45 tons



- **General good agreement in the stabilization of primary mass inventory → Water injection is compensated by the leakage at the break**

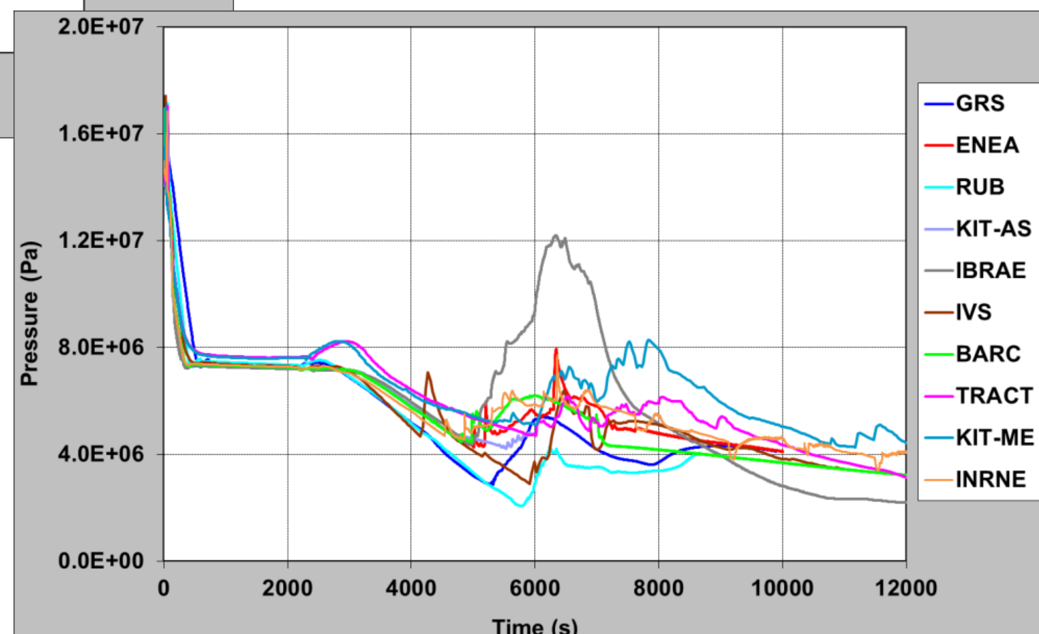
Reflooding Sequence Results (4 / 7)
Pressurizer Pressure



Degraded core mass = 10 tons

- The largest pressure peak is calculated by SOCRAT code also due to the much larger hydrogen production during reflooding

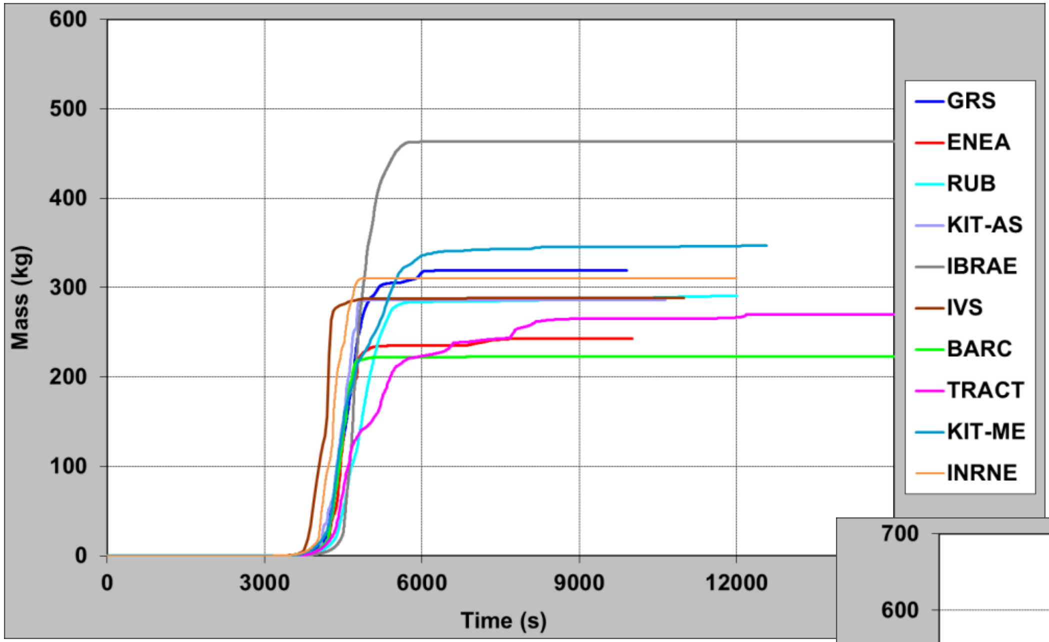
Degraded core mass = 45 tons



- All codes predict primary pressure increase at the onset of the reflooding phase mainly due to water/hot structure thermal interaction

Refllooding Sequence Results (5 / 7)

Cumulated Hydrogen Production



Degraded core mass = 10 tons

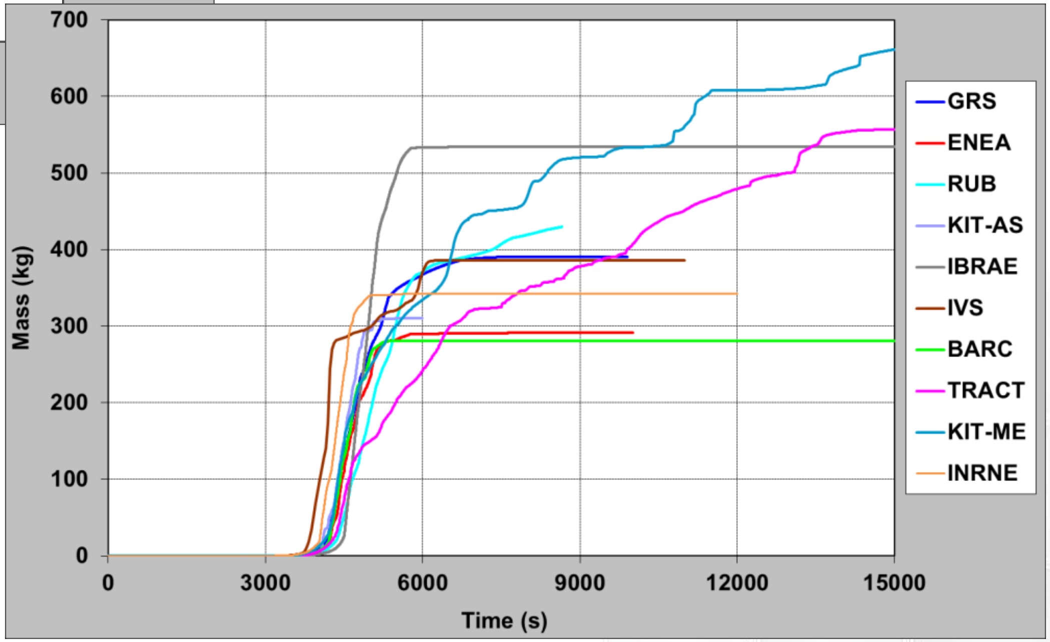
M = 10 tons (reflooding phase):

- **ASTEC → H2 is not very significant**
- **ATHLET → H2 is less than 100 kg**
- **MELCOR → H2 is about 100 kg**
- **SOCRAT → H2 is around 200 kg**

M = 45 tons (reflooding phase):

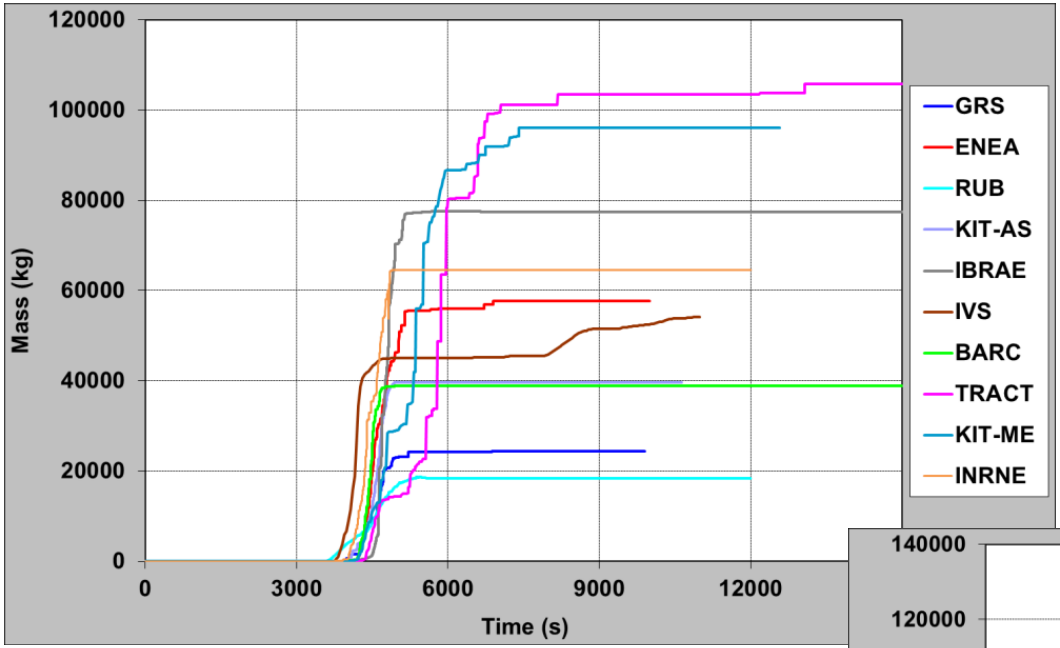
- **Similar behaviour to M = 10 t case except for progressive hydrogen production in MELCOR calculations**

Degraded core mass = 45 tons



Reflooding Sequence Results (6 / 7)

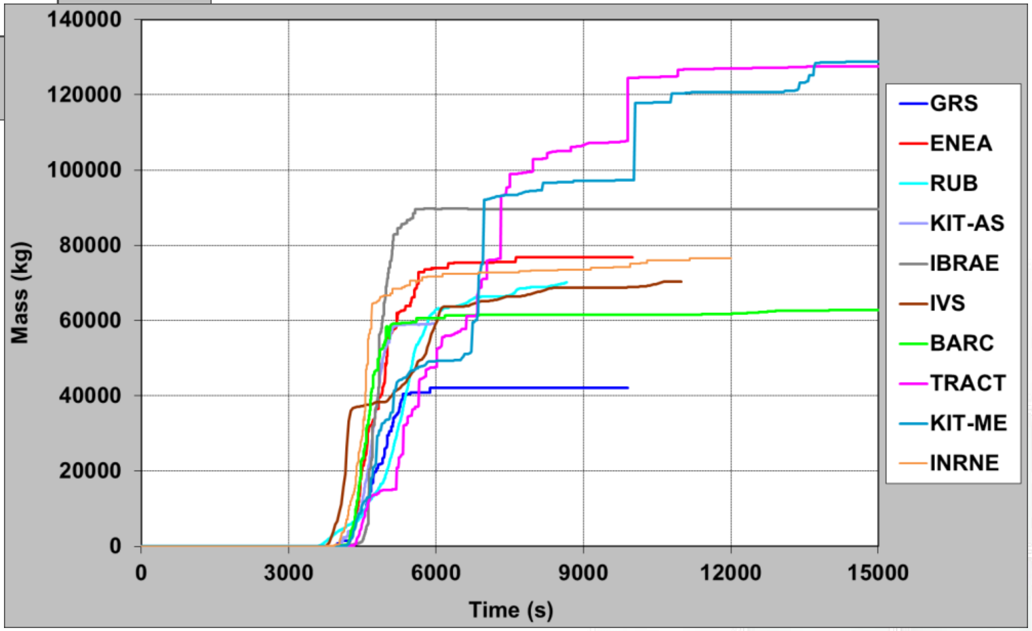
Total Mass of Degraded Core Materials



- **Large discrepancies in code results at the end of the reflooding phase**

Degraded core mass = 10 tons

Degraded core mass = 45 tons

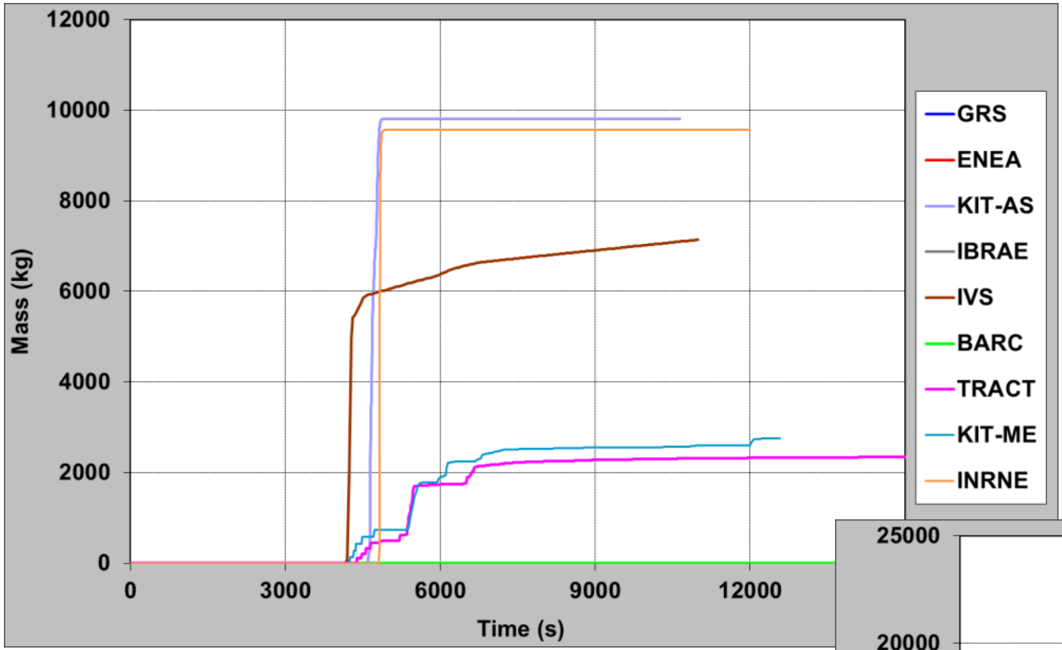


After onset of reflooding phase:

- **ASTEC and ATHLET → early stop of core melt progression**
- **MELCOR → latest stop of core melt progression**

Reflooding Sequence Results (7 / 7)

Total Mass Relocated in the Lower Plenum

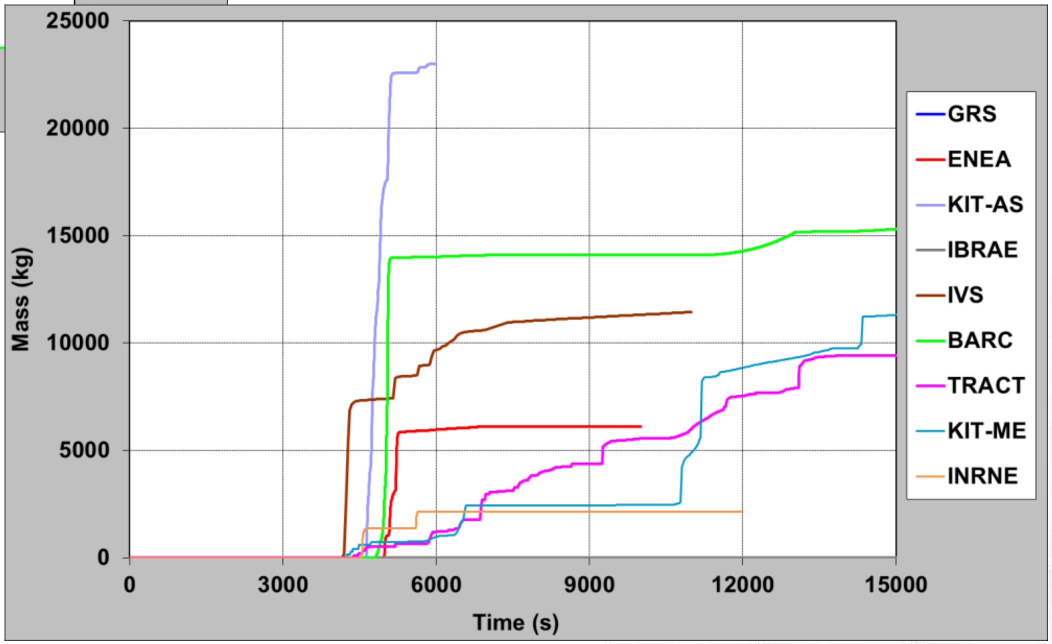


Degraded core mass = 10 tons

- No relocation or limited amount of molten material slumping in the lower plenum is predicted by all codes in both reflooding sequences

- No vessel failure is predicted by all codes in both reflooding sequences

Degraded core mass = 45 tons



SBO Sequence Calculation

- The 2nd sequence that was selected for code-to-code result comparison is a Station Blackout (SBO) scenario + surge line break
- INITIATING EVENT: Loss of offsite power supply + surge line break
- At time = 0 s → Reactor scram, primary pump trip, turbine and FW trip
- BOUNDARY CONDITIONS:
  - No letdown, no make-up flow and no HPI on primary side
  - No auxiliary feedwater on secondary side
  - Evolution of containment pressure seen at the break by GRS with ATHLET code
- Free evolution of the transient until vessel failure
- Investigation of core reflooding during low primary pressure scenario
- Two reflooding sequences have been defined like for the SBLOCA scenario → reflooding starting at M = 10 tons and M = 45 tons (M = degraded core mass) at different water injection rates (low and high injection rates)

Conclusions (1/2)

- Within the current benchmark exercise on TMI-2 plant, SBLOCA and SBO sequences are calculated by several organizations using different mechanistic and integral codes
- The performed calculations confirm the general robustness of the codes → All the codes were able to calculate the accident sequence up to the more severe degradation state and under degraded core reflooding conditions
- Thanks to the harmonisation of the initial steady-state and boundary conditions, the uncertainties on the prediction of the plant thermal-hydraulic behaviour have been minimized, at least before significant core degradation takes place

Conclusions (2/2)

- The deviation in code results becomes more remarkable after important core melting and relocation, involving the loss of rod-like geometry, fuel rod collapse and debris bed and molten pool formation, mainly due to:
  - Different core degradation models used by the codes, particularly in the late degradation phase
  - Some differences in the plant and core discretization
  - Different value chosen for core degradation parameters in input to the code
  - The last two effects are strictly connected with the user effect, and might be enhanced by the degree of freedom left by the code developers in the selection of code input parameter values
- The importance of precise code user guidelines is then strengthened, at least for reducing the differences between users of the same code
- The uncertainties on the calculation of the reflooding scenarios are still rather large, especially in case of later core reflood