



NUGENIA+ WP6.8

AIR-SFP Spent Fuel Pool behaviour in loss of cooling or loss of coolant accidents

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NUGENIA is mandated by SNETP to coordinate
nuclear Generation II & III R&D



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Introduction

- **Spent fuel pools (SFPs):** large structures equipped with storage racks designed to temporarily store irradiated nuclear fuel removed from the reactor
- **SFP severe accidents** have long been considered as highly improbable
- However, **the accident at the Fukushima Dai-ichi NPPs** has highlighted the vulnerability of nuclear fuels that are stored in SFPs in case of prolonged loss of cooling accidents and **renewed international interest in the safety of SFPs**
- **Questions about the reliability of the simulations performed with Severe Accident (SA) codes** since these codes were initially developed for reactor applications



*Underwater conditions in the SFP4,
(Image from video courtesy TEPCO)*

Objectives

- To assess more precisely the applicability of SA codes to the calculation of transients in SFPs in the frame of a benchmark, including a criticality risk assessment
- To elaborate a roadmap for further R&D on SFP accidents, both on phenomenology and on applicability of codes. The roadmap is based on SOARs on corresponding phenomena like oxidation, convective flows and criticality during SFP accidents



15 Participants from 14 countries

Participant organisation name	Short name	Country
Institut de Radioprotection et de Sûreté Nucléaire	IRSN	France
Centro de Investigaciones Energeticas Medio Ambientales y Tecnológicas	CIEMAT	Spain
Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	ENEA	Italy
Tractebel Engineering (GDF SUEZ)	ENGIE	Belgium
Gesellschaft für Anlagen- und Reaktorsicherheit mbH	GRS	Germany
Jozef Stefan Institute	IJS	Slovenia
Inzinierska Vypoctova Spolocnost Trnava s.r.o.	IVS	Slovakia
Karlsruhe Institute of Technology	KIT	Germany
Lithuanian Energy Institute	LEI	Lithuania
Nuclear Research & Consultancy Group v.o.f.	NRG	Netherlands
NUBIKI Nuclear Safety Research Institute	NUBIKI	Hungary
Paul Scherrer Institut	PSI	Switzerland
Risk engineering LTD	REL	Bulgaria
State Scientific and Technical Center for Nuclear and Radiation Safety	SSTC NRS	Ukraine
UJV Rez, a. s.	UJV	Czech Republic



- **WP 1 : Benchmark of SFP transients with SA codes (PSI coordination)**

Task 1.1

Analysis of SFP transients carried out in the frame of a benchmark on SFP geometry similar to Fukushima one

Task 1.2

Investigation of criticality phenomena that are usually not taken into account by SA codes: Analysis of the configurations that will potentially lead to criticality and thus to a power excursion

- **WP 2 : Roadmap for further R&D on SFP accidents (NRG coordination)**

To define more precisely needs on R&D and studies on : large-scale flow convection and the impact of partial dewatering, criticality

- **Geometry: Fukushima unit 4 spent fuel pool**
- **Scenarios:**
 1. boil down
 2. loss of coolant accident with constant water drainage (2.5 cm diameter and 2 m long vertical pipe connected through the bottom of the SFP, drainage in ≈ 3.5 d)
- **6 Codes used, 14 participants for the SA benchmark:**

ASTEC, ATHLET-CD, MELCOR, RELAP5, SCDAP, SPECTRA

Participants: ENEA, LEI, NUBIKI, IRSN, PSI, UJV, REL, IVS, ENGIE, SSTC, CIEMAT, GRS, IJS and NRG
- **Participants to the criticality analysis: ENEA, KIT, GRS and LEI**



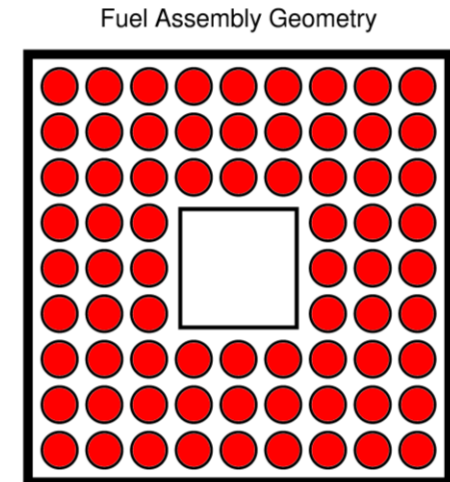
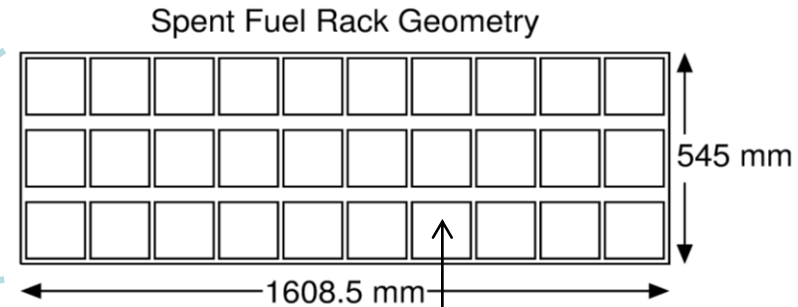
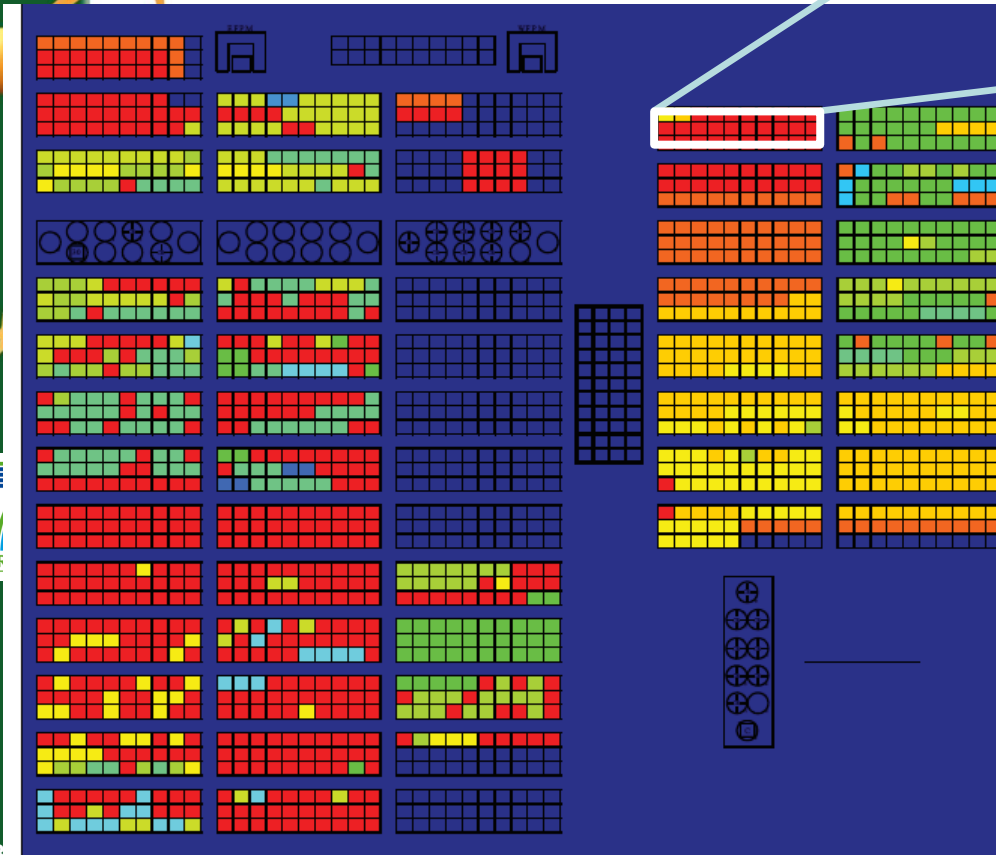
Results / WP1

SFP: 12.2 m × 9.9 m

Total heat load: 2.4 MW

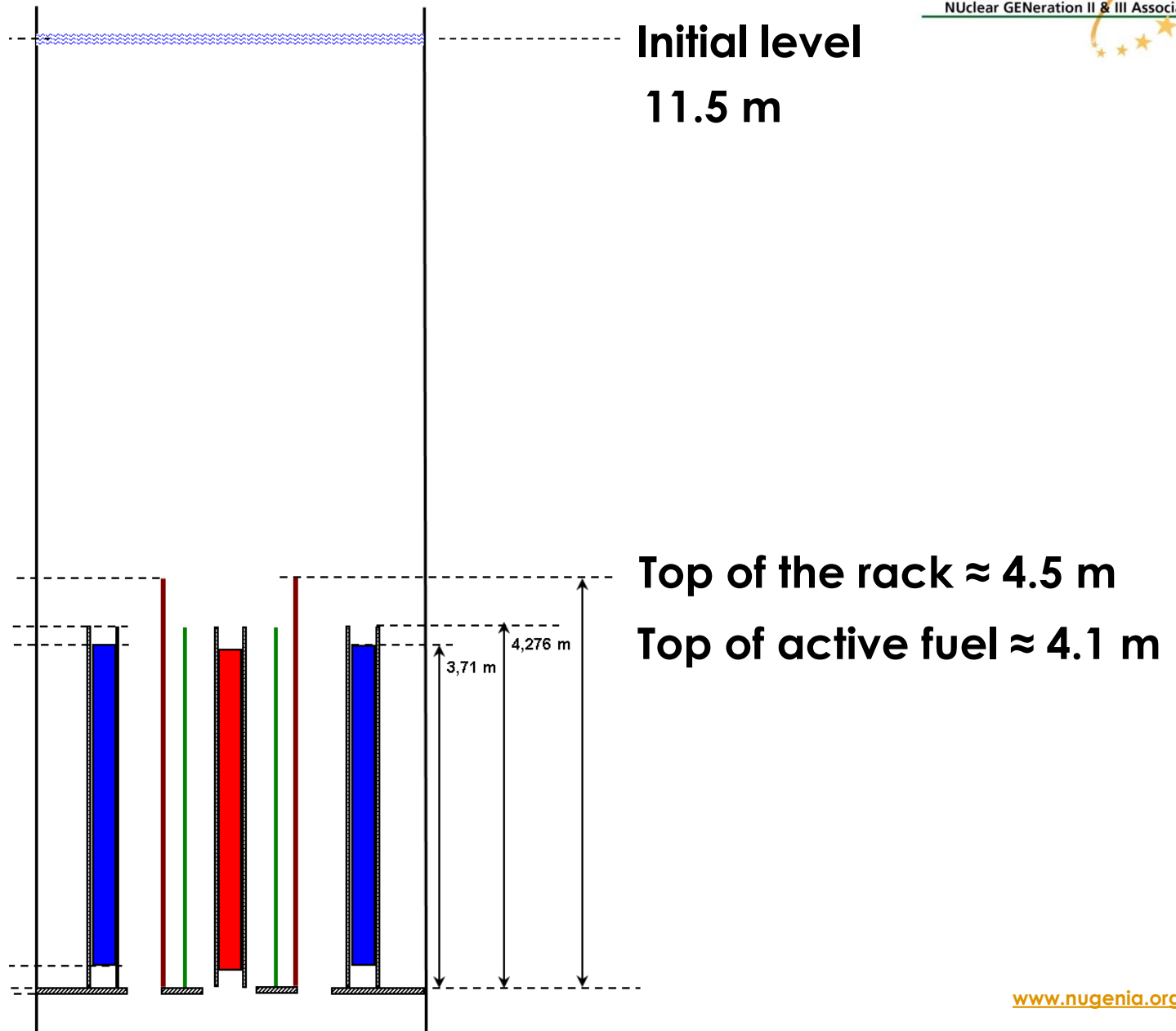
1535 FA: 548 hot, 783 cold, 204 fresh

Initial T°: 30°C (air), 40°C (water)



9*9-9 FA

Results / WP1

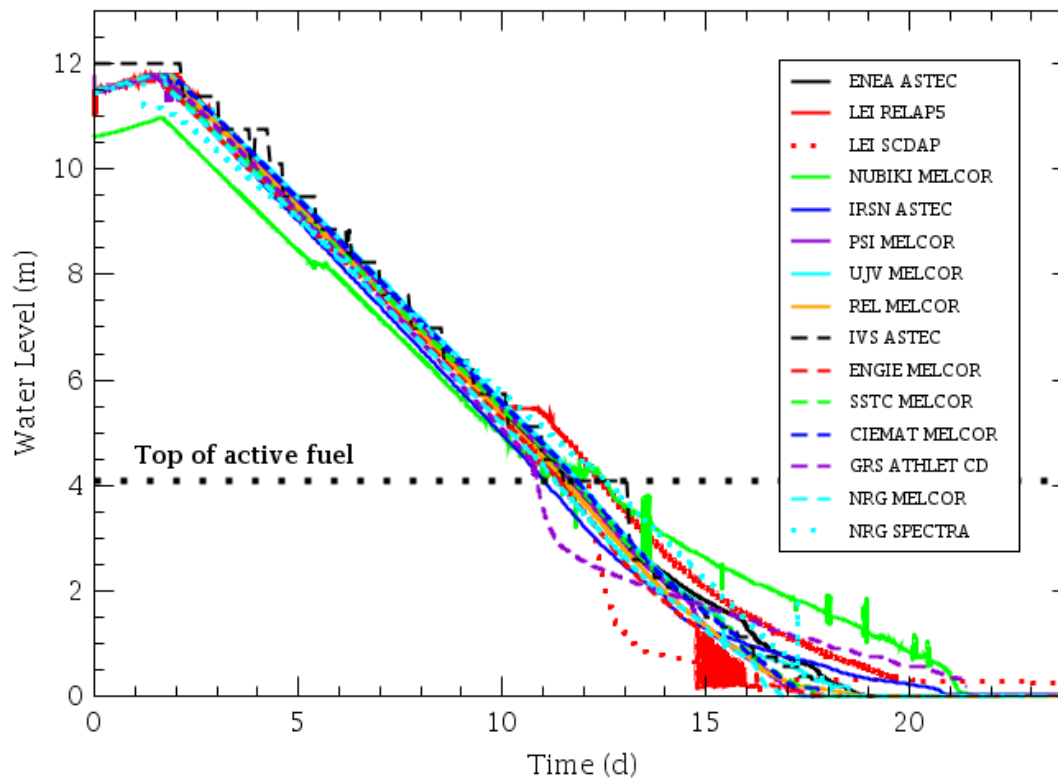


Evolution of the collapsed water level in the SFP (boildown)

Time to reach boiling between 37 h and 45 h

Time to reach the top of the rack between 10.6 days and 12.0 days. The top of active fuel is reached \approx half a day later

Good agreement in the slope of the curves until the water level drops below the top of the racks



Results / WP1 / SA benchmark

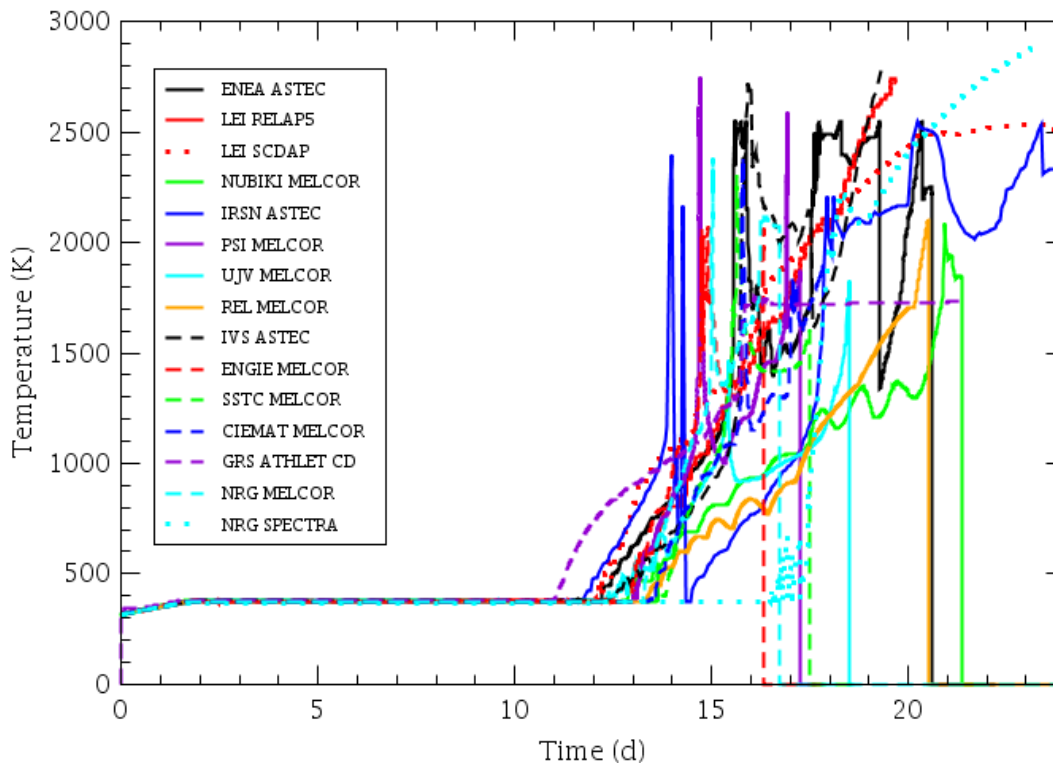
Evolution of the the peak cladding temperature (PCT) of the recently unloaded core (boildown)

Relatively **small \neq** in times of onset of the heat up

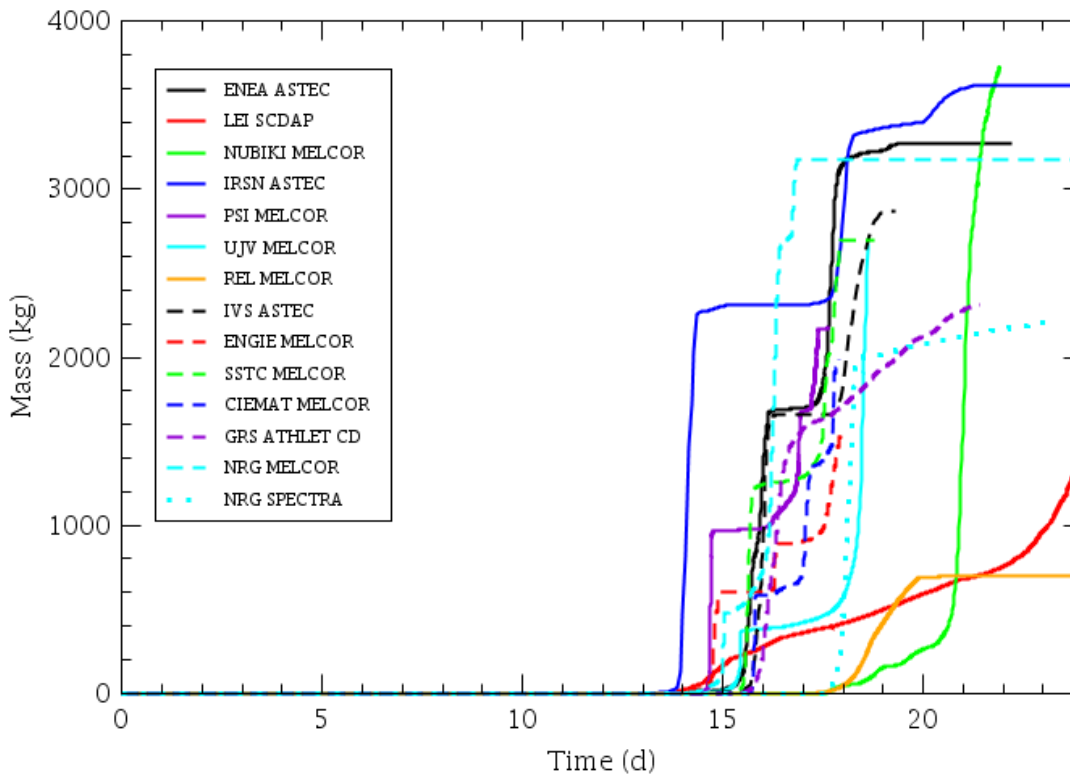
Large spreading in the heating rate (**170-480 K/d**)

T° escalation when the T° reaches **1000-1200 K** (for some participants)

Wide spreading in the T° of the longer stored spent fuel due to \neq modeling of the heat transfer between the FAs



Evolution of integral hydrogen production in the spent fuel pool (boildown)



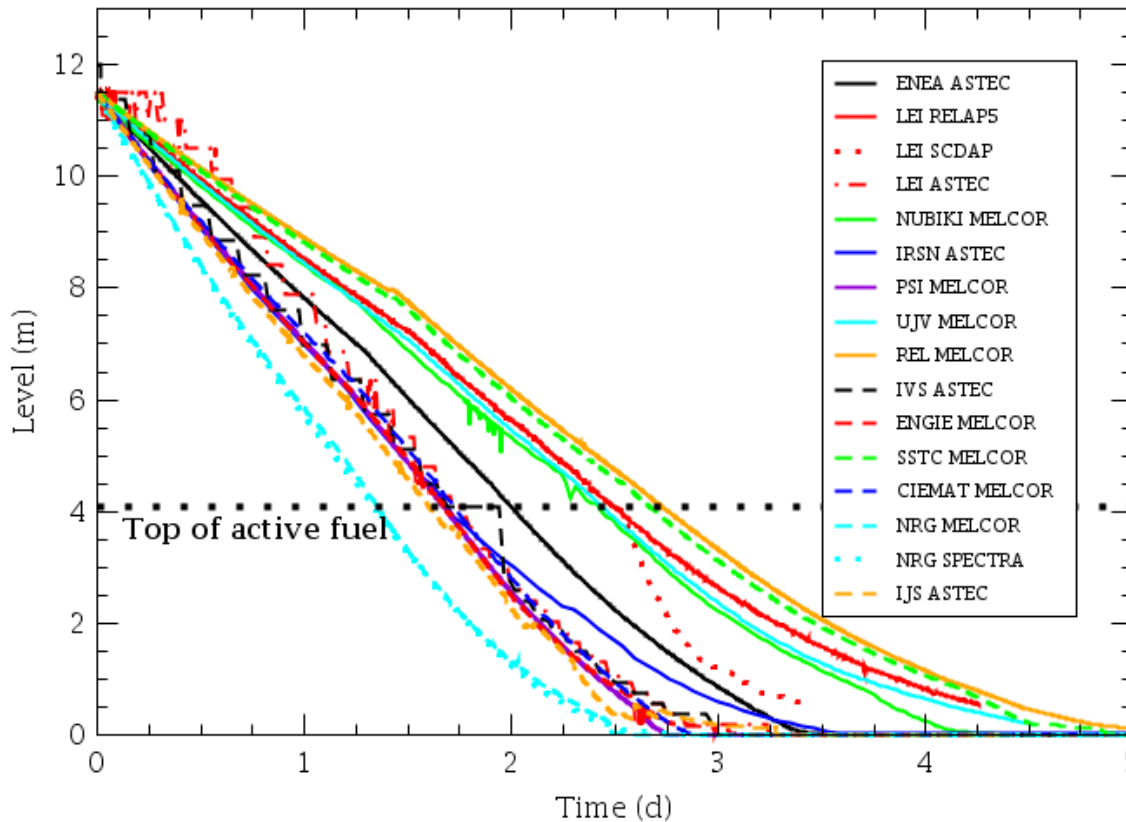
Start of H₂ production when T° reaches ≈ 1200 K : large scattering (13.5-17.5 days)

At that time, the water level is ≈ 1.5 m (2/3 of the active fuel uncovered)

Very Large scattering of total H₂ production - at minimum 1.4 tons of H₂ (except the REL-MELCOR calculation: 0.7 ton)

Start of H₂ production ≈ time of first fission product release (gap release)

Evolution of the collapsed water level in the SFP (LOCA)

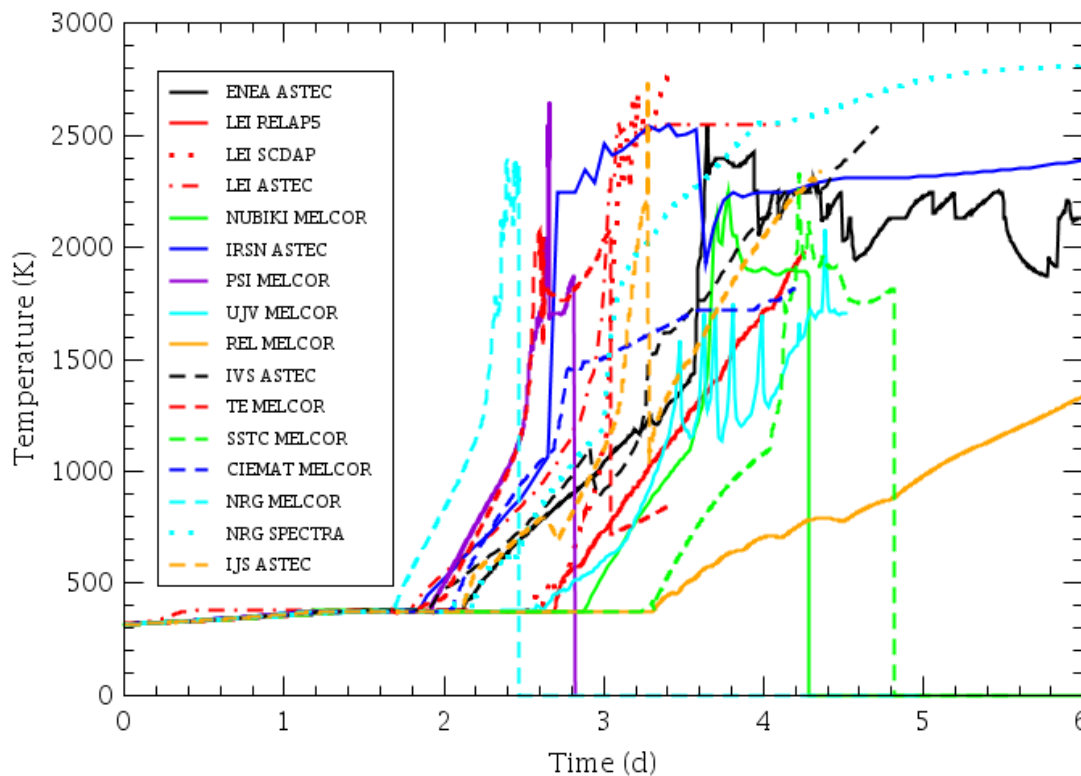


Wide range of results for the draining velocities (\neq due to the modeling of the pipe)

From the total water mass of about 1300 tons about 90 % is lost by draining

Results / WP1 / SA benchmark

Evolution of the peak cladding temperature (PCT) of the recently unloaded core (LOCA)

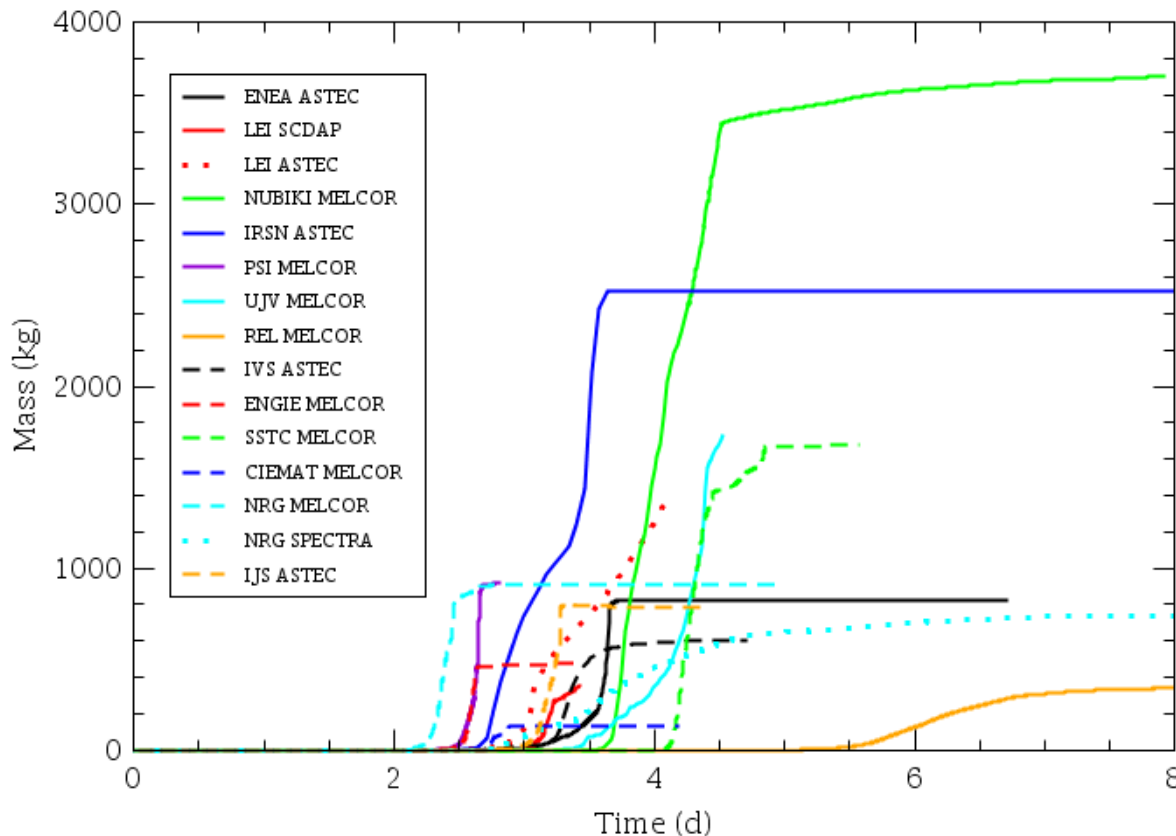


The PCT shows a wide range of distributions (due to the difference in draining velocity)

The onset of heat up ranges between 1.6 and 3.3 days

The heat up velocity is faster by a factor between 2.5 and 3 (for most participants) in comparison with the boildown scenario

Evolution of integral hydrogen production in the spent fuel pool (LOCA)



Amount of H₂ produced not remarkably ≠ from that of the boildown calculations, but in principle a bit less

In case of a very fast pool drainage, T° might not reach high levels before no more water and/or steam is available, so that much less H₂ would be produced

Conclusions of the SA benchmark:

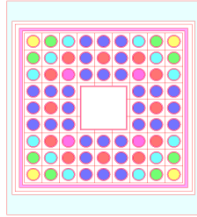
- **The onset of heat-up (strongly linked with the collapsed water level) in rather good agreement for the boildown scenario but not for the LOCA scenario (wide range of draining velocities)**
- **For both scenarios, the heating rate of hot FAs differs by a factor of 3 (even larger scattering for cold FAs) → important spreading of the onset of fuel melting**
- **The total amount of hydrogen produced differs significantly by a factor of 5 for the boildown scenario and by a factor of 10 for the LOCA scenario**



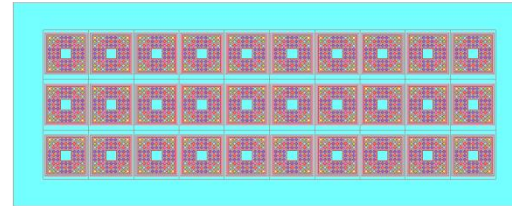
Results / WP1 / Criticality analysis

ENEA Results (KENO VI Monte Carlo code)

UC



RS



Reference conditions
($\rho=1 \text{ g/cm}^3$ and $T=25 \text{ }^\circ\text{C}$)

System	K_{eff} (-)	Std (pcm)
Central Unit Cell (UC)	0.84556	84
Full Rack10x3 (RS)	0.78478	25

Accidental conditions (non-uniform fuel temperature and water density axial profile due to dewatering - Decay power of 9 kW \approx 15 days after shutdown)

Case	K_{eff} (-)	Std (pcm)
RELAP5/KENO VI	0.81935	30

↑ in k -eff from about 0.785 to about 0.819 (increased neutron coupling between FAs due to the decrease of water absorption)

The safety limit (0.95) may be exceeded if reactivity increase due to Gadolinium depletion is added (accidental conditions not met in the SA benchmark with a decay power < 3.5 kW / hot FA)

Lessons learned from the benchmark

Scattering in the results is due to:

- **Strong differences in modeling assumptions (with the same code)** → different modeling of the racks configuration and consequently of the rack-to-rack heat transfers
- **Differences in the computation of the hydraulic resistance of FAs** → differences in the steam velocity and consequently in the FAs cooling
- **Differences in the modeling of the cladding oxidation under a mixture of steam, oxygen and nitrogen that drives the heat up** → can be another reason for scattering of the results for the temperature range where oxidation is significant (above around 900°C)
- **Differences in the boundary conditions** → strong influence of the modeling of the building above the pool and of the pipe used to drain the pool



Recommendations for future R&D activities (based on the SA benchmark, the criticality analysis and the SOAR about phenomena during SFP accidents):

- **SA codes can be used for SFPs application only with a careful examination of modeling assumptions**, a deep understanding of simulated processes and considering the high uncertainty of simulation results → it is thus recommended that each code provides guidelines for the modeling of the SFP geometry
- For heat transfer, a modeling taking into account FAs arrangement in the racks should be developed in SA codes
- Concerning the **oxidation/nitriding phenomena**:
 - a lot of experimental data already exist, more data are needed for conditions prototypic for SFP accidents
 - modeling must be improved to integrate recent progress made in phenomenological understanding. Difficulties arise from the high number of parameters and from the fact that these parameters, that are usually set constant in experiments, varied in an accident scenarios.

- **Flow conditions during SFP accidents** → couple SA codes (to model the physics in the FAs where the flow is 1D) and CFD (to provide the gas flow outside the racks). Would require important efforts in code-to-code coupling, validation and verification
- **Criticality analysis** → calculation accuracy could be increased by using more realistic conditions, by using improved thermal-hydraulic calculations for accidental situations and by properly taking into account gadolinium depletion
- The phenomena should also be studied from an experimental point of view → it is therefore mandatory to identify and develop experiments to answer questions above-mentioned: **thermal-hydraulics at the scale of the FAs** (this issue is addressed in the French experimental program named DENOPI), **role of the various parameters involved in oxidation** under conditions prototypic of SFP accidental transients, **validation of criticality excursions codes** which currently are poorly validated for heterogeneous configurations (like FAs)



Planned presentations and conferences:

CSARP meeting, September 13-15, 2016 in USA (Bernd Jaëckel, PSI)

NENE conference, September 5-8, 2016 in Slovenia (Federico Rocchi, ENEA)

ERMSAR conference, May 16-18, 2017 in Poland (Olivia Coindreau, IRSN)

A publication will be prepared for a journal dedicated to the nuclear community like Nuclear Engineering and Design or Annals of Nuclear Energy.



- **Mutual information sharing on SFP issues and specifically on the level of uncertainty of SA codes when they are used for SFPs studies** → **useful for end-users such as industry (vendors, utilities), national safety authorities and their technical safety organisations**
- **Thanks to the roadmap, establishment of an efficient route to obtain in the long-term improved calculation tools, which will reinforce the capability of numerical methods to compute SA scenarios in SFPs**
- **The AIR-SFP conclusions will serve as useful inputs for the OECD/NEA/CSNI/WGAMA “PIRT (Phenomena Identification and Ranking Table) on SFP accidents”**



Conclusions

The project has contributed to reinforce research cooperation on reactor safety at EU level by bringing together research organizations, TSOs, utilities and designers. The benchmark exercise has been successfully conducted and the roadmap will contribute to define new R&D projects.

Next steps

All the outcomes of WP2 may be used to propose a new R&D project on this SFP issue, either in OECD frame or in the next H2020 Call.

