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DENOPI PROJECT DEVOTED TO SPENT FUEL POOL ACCIDENTS: OVERVIEW ON THE THERMAL HYDRAULICS EXPERIMENTAL FACILITIES

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DENOPI PROJECT DEVOTED TO SPENT FUEL POOL ACCIDENTS: OVERVIEW ON THE THERMAL HYDRAULICS EXPERIMENTAL FACILITIES

Outline

- Introduction and context : spent fuel pool accidents
- Thermal hydraulics at the spent fuel pool scale: MIDI facility
- Thermal hydraulics at the fuel bundle scale: ASPIC facility
- Conclusions & next steps

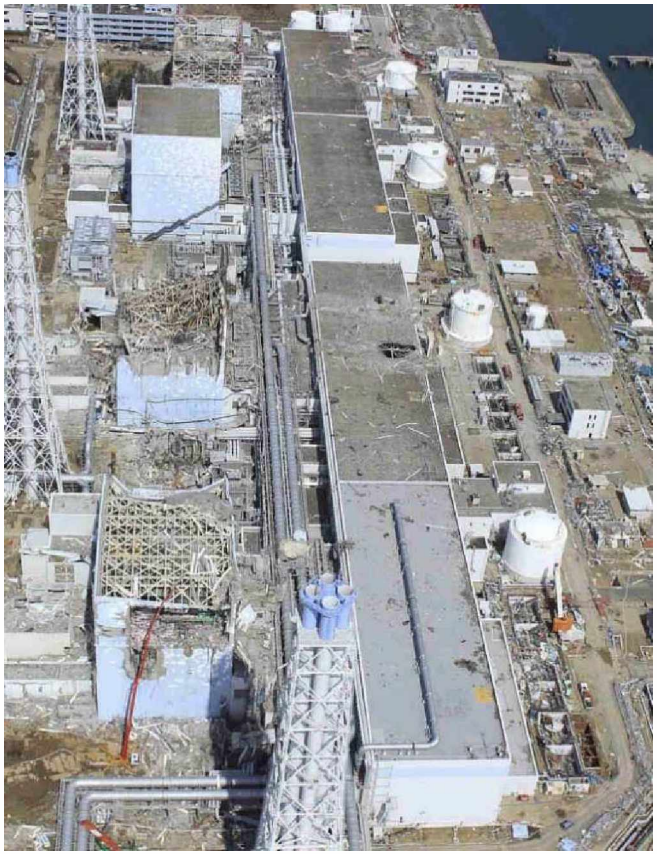
DENOPI PROJECT DEVOTED TO SPENT FUEL POOL ACCIDENTS

Elements of context

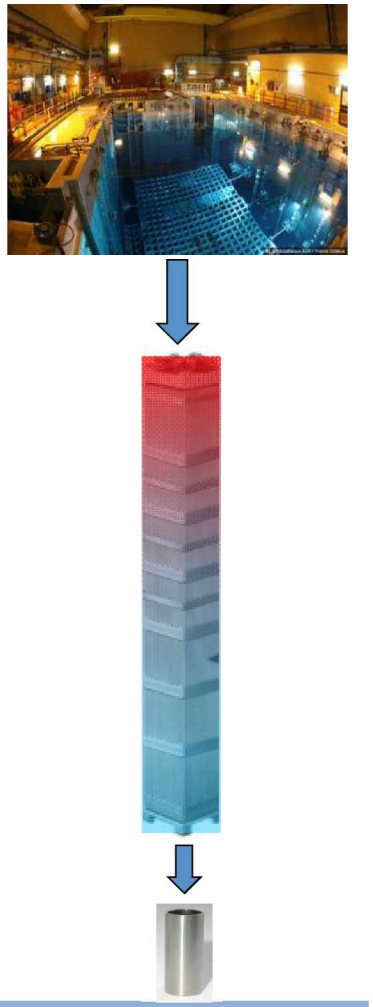
- Fukushima Daiichi Unit 4 (March 11, 2011): 1331 spent fuels/2.26 MWth ⇒ Spent fuel pool loss of cooling triggered international efforts on SFP accidents

- At the light of the accident, active international works on SFPs :
  - OECD : Status report on SFP under loss of cooling and LOCA conditions (2015)
  - OECD : Phenomena Identification and Ranking Table on SFP-LOCA (2018)
  - European Community : stress tests program, benchmark of SFP transients with SA code
  - ….

- France : call for projects from the National Research Agency
  ⇒ **DENOPI PROJECT (2014)**



DENOPI project : overview

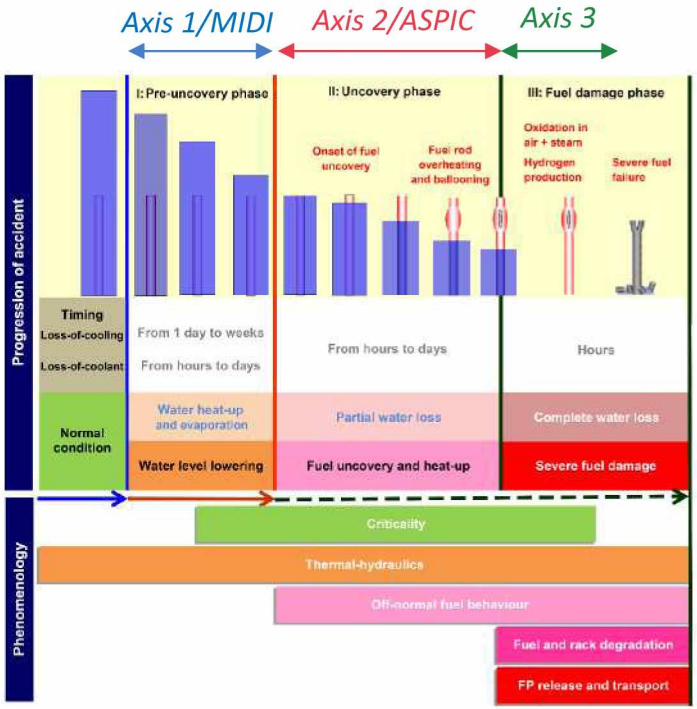


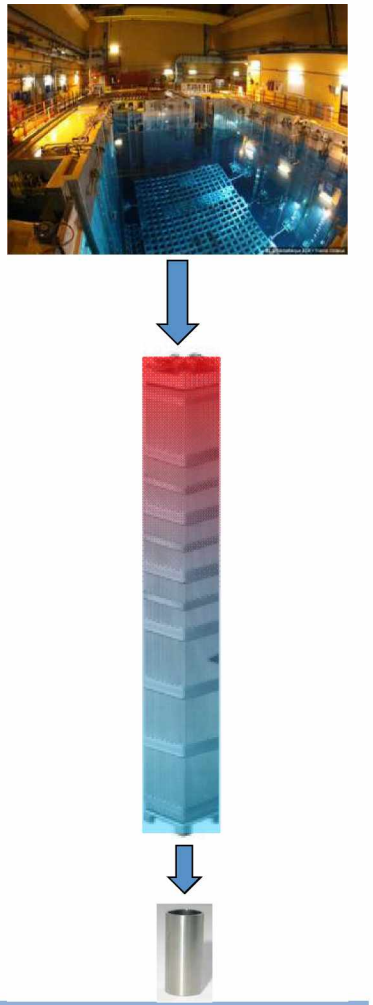
- Framework: post-Fukushima project, supported by the French government (ANR 11 – RSNR 006) – 2014/2022

- Participants: IRSN, French academic labs, national and international partners

- Organizer in 3 axis representing both different time frames of the accident and different scales of interest
  - Axis 1 at pool scale: before fuel uncovery ⇒ **MIDI facility**
  - Axis 2 at assembly scale: partial or total uncovery of fuel assembly ⇒ **ASPIC facility**
  - Axis 3 at fuel clad scale: clad degradation after uncovery

DENOPI project : overview

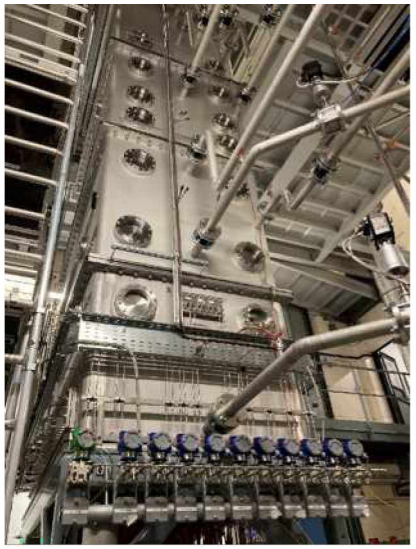




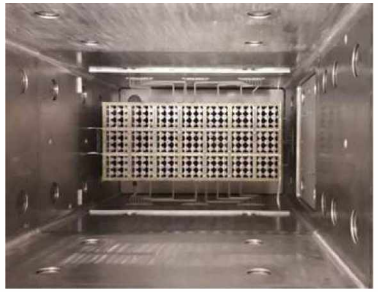
Temporal phases and phenomenology of SFP loss-of-cooling/coolant accidents*

**figure extracts from the PIRT's report on SFP accidents*

THERMAL HYDRAULICS AT THE SPENT FUEL POOL SCALE: MIDI facility



MIDI basin without the thermal insulation



Top view of the rack at the basin's bottom

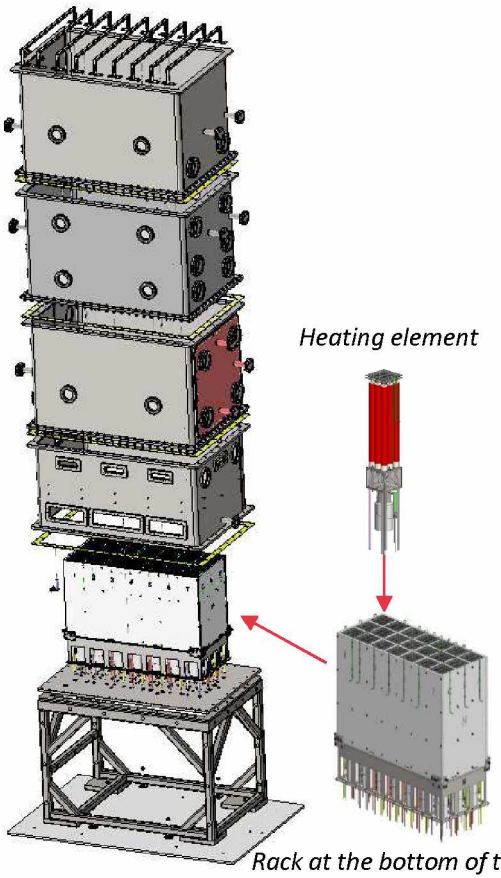
Main targets

- Get a better understanding and an experimental data base on the TH behavior of a SFP in case of a loss-of-cooling accident before FA uncover : study of coupled natural convection flows and vaporization regimes
- Contribution to the validation of models and computer codes
- Application to at-reactor SFPs, but also to away-from-reactor SFPs

Mock-up of a typical French 900 Mwe SFP at reduced scale (1/6th except for the pool height 1/3rd and heating power)

Parameters	MIDI facility	Typical PWR SFP	Scale ratio
Maximum water level (m)	4.0	12.0	1/3
Bundle active length (m)	0.7	~ 4.0	~ 1/3
Basin width (m)	1.42	8.50	1/6
Basin length (m)	2.10	12.60	1/6
Overall rack flow section (m²)	0.65	22.86	~ 1/35
Free surface area (m²)	2.982	107.1	~ 1/36
Bundle width (m)	0.225	0.225	1/1
Bundle porosity (-)	0.61	0.57	~ 1/1
Number of cells (-)	21 (7 X3)	792	~ 1/37
Power range (kW)	[50;300]	10 000	-
Max. power per bundle (kW)	50	58	~ 6/7
Volumetric power (kW/m^3)	[4.2;25.1]	7.8	-

THERMAL HYDRAULICS AT THE SPENT FUEL POOL SCALE: MIDI facility



Rack at the bottom of the basin with 3X7 cells

Main characteristics

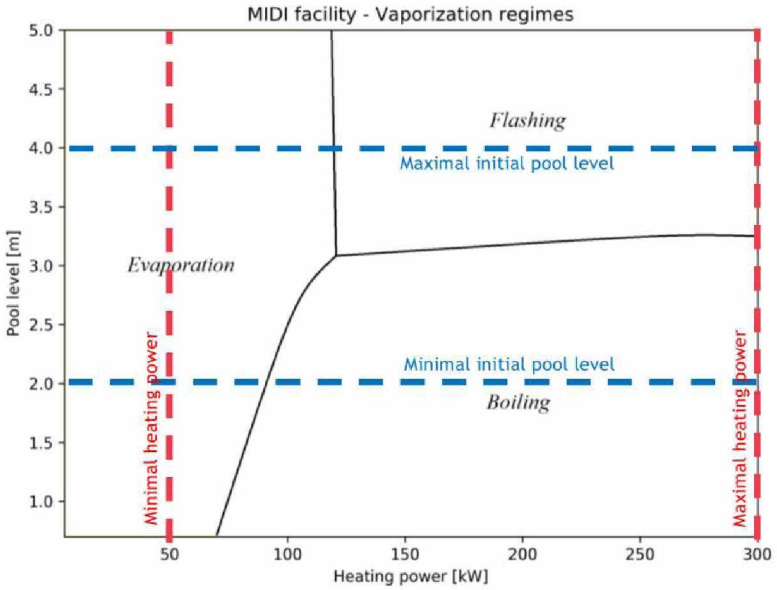
- Power of fuels simulated with electrically heated rods
  - 21 individual heating elements represent 21 cells of a storage rack - regular arrangement of the cells : 3X7
  - An heating element comprises an heated rods bundle (3X3)
- Control of the boundaries conditions
- Atmospheric volume above the free surface (suction hood extracting steam outside)
- Filling with demineralized water (until ~ 12 m^3)

Main instrumentation

- rack thermal-hydraulic characterization (fluid temperatures, flowrates at each cell, heating power)
- void fraction at each outlet cell
- fluid temperatures in the volume above the rack
- pool levels (collapsed and swelled)
- water quality : conductivity & dissolved O2
- gas temperature, absolute pressure, relative humidity of atmospheric volume above the free surface
- temperature of free surface
- temperature of lateral insulated walls

THERMAL HYDRAULICS AT THE SPENT FUEL POOL SCALE: MIDI facility

Test matrix based on 4 parameters

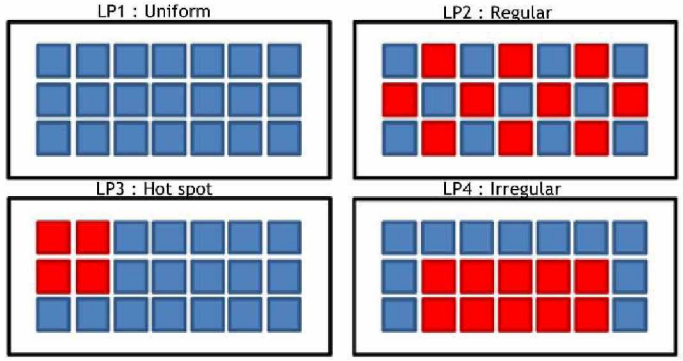


3 main vapor formation modes identified

- Evaporation at the free surface
- Nucleate boiling into the cells
- Flashing of superheated water in the upper part of the basin

↗ Pool level (1)

↗ Heating power (2)



↗ Loading pattern (3)

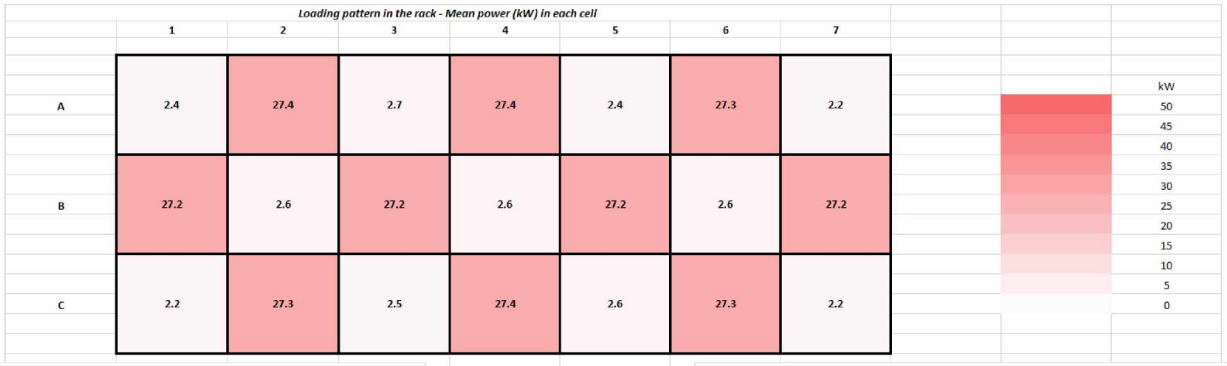
Reference	Type of loading pattern	"Hot cells"	"Cold cells"
LP1	"Uniform"	21 (100% overall power)	/
LP2	"Regular"	10 (91% overall power)	11 (9% overall power)
LP3	"Hot spot"	4 (91% overall power) or 4 (66% overall power)	17 (9% overall power) or 17 (34% overall power)
LP4	"Irregular"	10 (91% overall power)	11 (9% overall power)

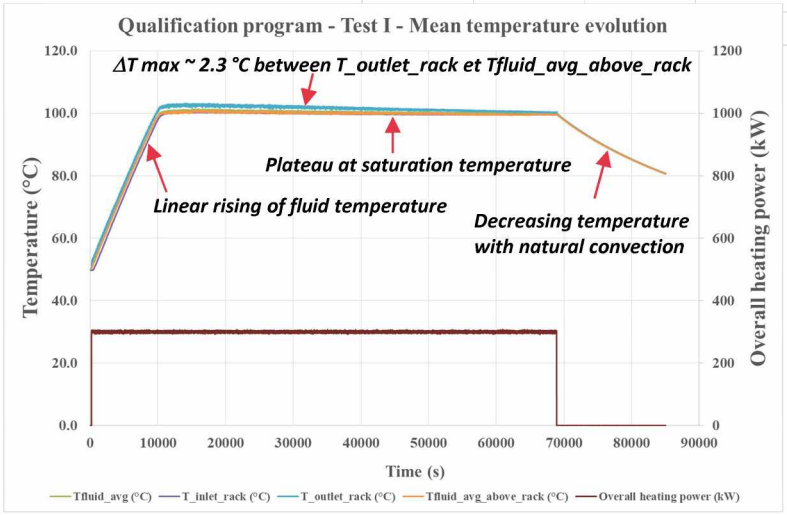
- Uniform loading pattern : ratio induced by the loading pattern
- 91% Hot -9% Cold : Management of SFP during shutdown in French 900 MWe : fuels under full-core discharged are moved into SFP
- Other ratios determined from an overall power of 300 kW and the maximum permissible power of a cell (50 kW)

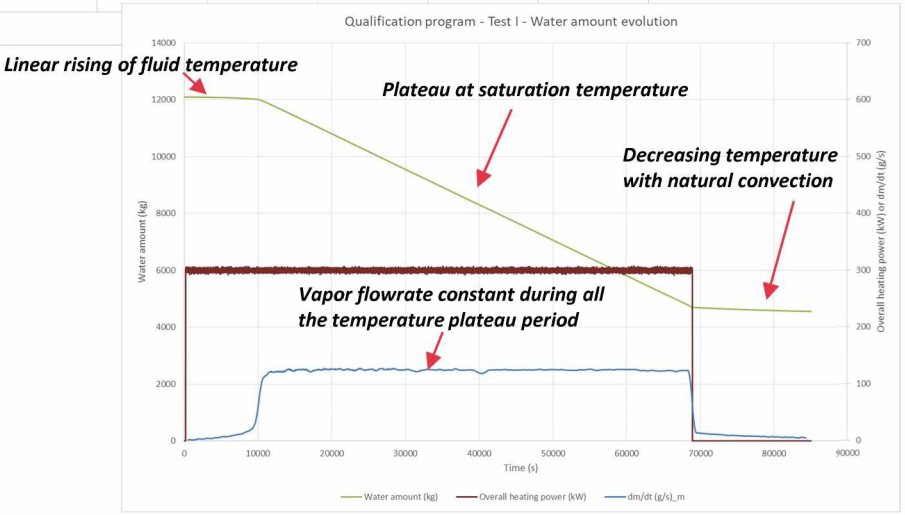
↗ Ratio of heating power between "hot" and "cold" cells (4)

THERMAL HYDRAULICS AT THE SPENT FUEL POOL SCALE: MIDI facility

Some results from qualification tests

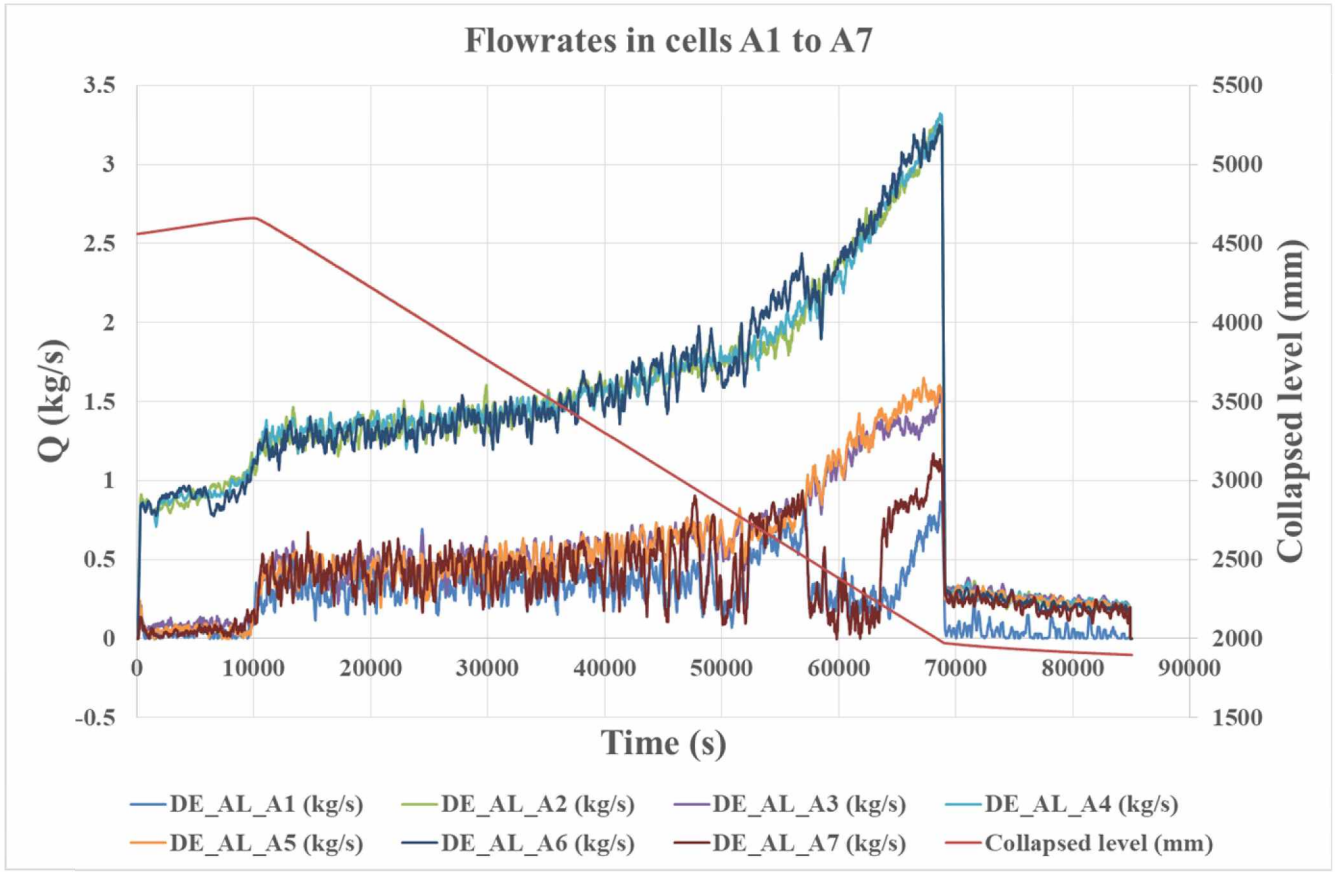






THERMAL HYDRAULICS AT THE SPENT FUEL POOL SCALE: MIDI facility

Some results from qualification tests



Main informations

1) Flowrates controlled by the power level in the cell

2) Flowrates evolutions seem showing also the different vaporization regimes

3) Increase of flowrates in the cells reflect the increase of the boiling in the cells

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility

Insertion of the bundle in the cell

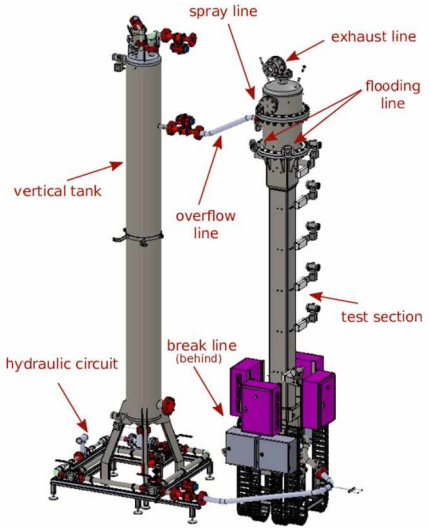
ASPIC facility in operation

Context

- Rod bundle stored in a spent fuel pool rack
- From boiling until the full uncover

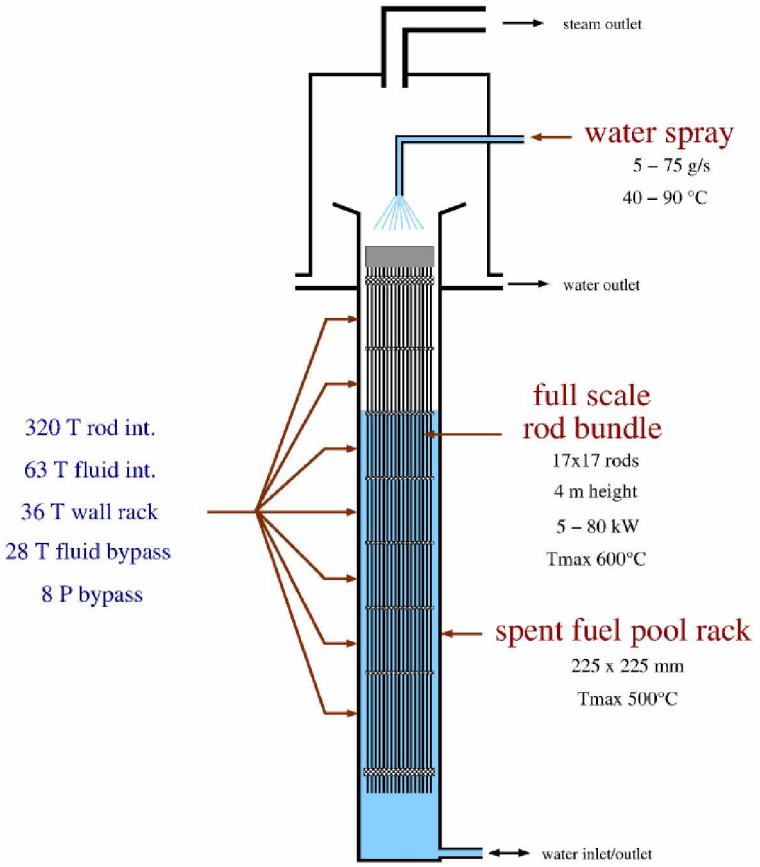
Main targets

- Assessment of the efficiency of a spray system to cool down a fuel assembly
- Analysis of the thermal exchanges during the bundle dewatering



Overview of the ASPIC facility

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility



Main characteristics

- Full assembly scale, 17x17 electrically heated rods
- Geometric characteristics of a standard PWR assembly
- Power range of fuel bundle : 5 – 80 kW
- Size cell framing the fuel assembly: square tube 225 X 225
- Versatile configuration: no, partial or total uncovering of fuel bundle
- Water spray from the top: 0 – 75 g/s, 40 - 90°C
- Thermal insulation of all external surfaces

Main instrumentation

- 8 pressure measurements in the test section for void fraction estimation
- Wall temperatures of the rack
- Fluid temperatures inside the fuel bundle and in the gap between the rack/fuel bundle
- 80 heating rods instrumented with 4 thermocouples : 320 rods temperatures
- Water temperature and mass flowrate in the spray line
- Steam outlet flowrate

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility

- Test matrix based on :
  - the comparison of tests carried out with/without the spray system
  - test scenario with a stabilized water level

A0 - Boiling with a stabilized water level
- Initial state: hot water (~100°C) at a defined level
- Warm-up of the rod bundle
- Stop the warm-up close to the maximum bearable (temperature of the rods ~ 500°C)

⇕ *Assessment of spray efficiency*

A1 - Spray cooling with a stabilized water level
- Initial state: hot water (~100°C) at a defined level
- Warm-up of the rod bundle
- Trigger of the spray on a rod temperature criterion (110°C)
- Stop the warm-up close to the maximum bearable (temperature of the rods ~500°C)

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility

Test matrix based on :

- a reference test and a parametric study around this reference test

Reference test and repeatability (scenario A) ➔ 6 tests

- Bundle power: 20 kW
- Water height: 3 m
- Spray mass flowrate: 5 g/s
- Spray temperature: 40°C
- Rod temperature at the spray trigger: 110°C

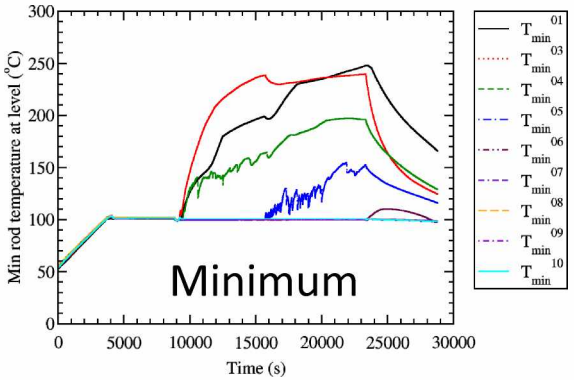
⇩

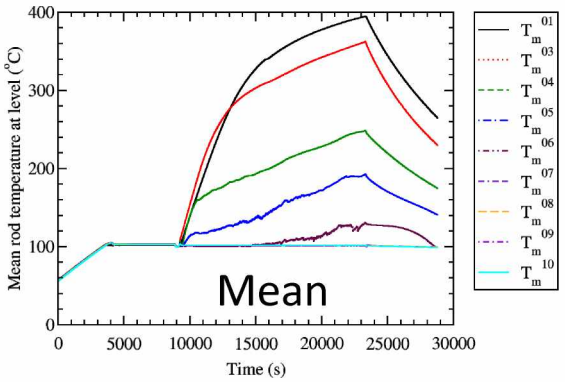
Variations around the reference test➔ 20 tests

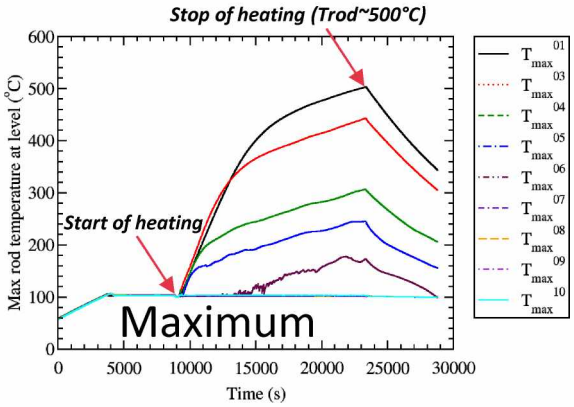
- Bundle power: 10, 40 and 60 kW
- Water height: 0,1 and 2 m
- Spray mass flowrate: 10, 15 and 25 g/s
- Spray temperature: 80°C
- Rod temperature at the spray trigger: 200, 300 and 400°C

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility

- Typical results with test A1



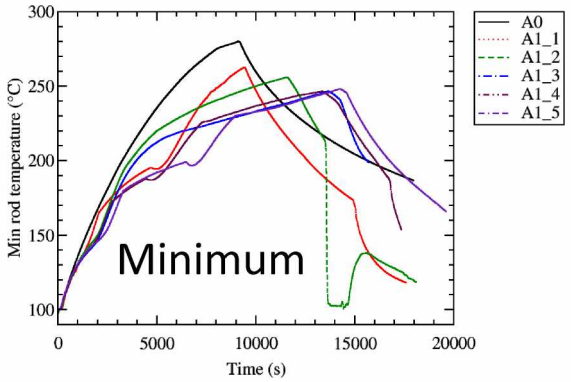


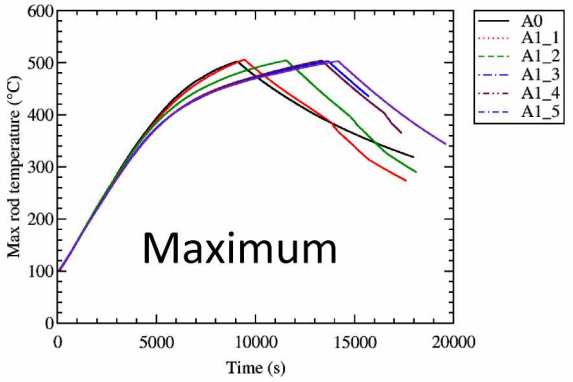


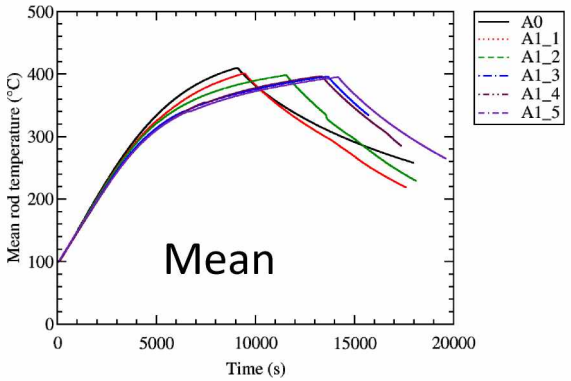
- Spray trigger at 110°C
- Rods temperature statistics evolution with time at the upper levels

THERMAL HYDRAULICS AT THE FUEL BUNDLE SCALE: ASPIC facility

- First results : comparison with/without spray (Tests A0/A1)







- Time to reach 500°C is increased by about 50% with the spray (without taking into account A1_1 & A1_2 where water level not well stabilized)
- Estimated temperature plateau
  - Without the spray: 673 °C
  - With the spray: 523 °C

CONCLUSIONS & NEXT STEPS

- Two new facilities, devoted to spent fuel pool accidents, were implemented in IRSN laboratories at Cadarache Center
  - MIDI: study of thermal hydraulic phenomena at pool scale before the fuel uncovery stage
  - ASPIC: study of thermal hydraulic phenomena at fuel assembly scale before fuel degradation
- Experimentations in MIDI are now in progress, test report is expected by the end of 2022
- First experimentations in ASPIC are finished and first benchmark of the results with IRSN's DRACCAR code is in progress (tests without spray)
- End of DENOPI project is scheduled for the end of 2022, to date it is planned to continue the experiments and to propose a project as an OECD/NEA/CSNI Project for the 2023-2026 period.