Irradiation Facilities and Examination Benches for Implementing Fuel Programs in the Future Jules Horowitz MTR

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- An experimental capacity driven by users needs
- From fuel development process to experimental requests
- Status on fuel hosting systems under development
- Non destructive examination benches
- Conclusions
The JHR: A new MTR in Europe

- A new MTR is under construction in Europe since about 40 years
- Unique opportunity to design a whole irradiation device park
  - In a modern safety frame
  - Targeted to offer maximum information during the experiment (on-line)
  - To fulfill end-user needs for several decades

- To identify the future needs for a suitable design is mandatory… but not so easy!
  - Long term needs (> 2015) are generally not expressed
  - Identified short-term needs shall be solved in the coming years

Milestones of a fuel product development process

Identification and evaluation work

Expected R&D needs and associated time-frame

Nuclear fuel « landscape » after 2015

MTRs
Hot cells etc.
Milestones of a fuel product development process in MTR

Selection / Characterization

- Fuel material knowledge
  - Input data for modeling
  - Microstructure selection

- Behavior understanding
- Laws and models set-up
  - Separate effect experiments
  - Instrumented samples
  - On-line measurements
  - Adapted LHGR time histories

10-15 years

Qualification / Safety tests

- Tests on industrial products
  - Very high burn-ups
  - Soliciting LHGR time histories
  - Failed fuel rods
  - Operation at the limits (ramps, lift-off, LOCA-type, ...)
  - Accidental situations (RIA, FCI, ...)

- Test of industrial products
  - One single fuel rod

Material studies

- Numerous samples

Scientific stakes (Research, Fuel vendors)

Operational stakes (Research, Utilities, Fuel vendors)
Why are fuel irradiations in MTRs necessary for supporting the fuel development process?

**Simulation tools are often not sufficiently validated when:**

- Fuel product is improved, or is planned to be used beyond current operating conditions
- Fuel reliability shall be more proven
- Safety criteria have been changed

**Fuel product is not allowed to be irradiated in a power plant (as a precursor)**

- Envelope use conditions
- Operating domain not reachable by a power reactor
- Reactor not existing

⇒ Need to support technical and safety assessment oriented licensing file (industrial partner often leader)

Knowledge valorization in simulation codes is a permanent driving force
Measuring fuel basic data: Need for a science-based approach strategy coupling MTR, hot labs, large facilities and modeling

Out of pile experiments
Temp. effect
Chem. effect

<table>
<thead>
<tr>
<th>Ion Irradiations</th>
<th>Neutron (FP) Irradiations</th>
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<tbody>
<tr>
<td>Large Facilities (Accelerator)</td>
<td>MTR</td>
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Fine characterization
before, after or under irradiation

Multiscale characterization thanks to:
- Hot Lab Facilities: TEM, SIMS, EPMA, XRD...
- Large Facilities / Synchrotron XAS, XRD,
  ⇒ Soleil: a specific beam line for irradiated fuel: Mars BL
What will be the nuclear fuel landscape after 2015?

**Expected fuel product evolutions (trends)**

- Doped UO$_2$ or UO$_2$ with high content of neutronic absorbers (Gd, Er…)
- MOX with high Pu content or UO$_2$ with high $^{235}$U enrichment (> 5%?)
- Innovative UO$_2$ or MOX fuel (geometry, microstructure)
- Triplet {fuel material, pellet geometry, clad material} optimization
- Etc… (specific needs)

**Examples of expected issues for improving fuel reliability**

**Challenges**

- Power ramps behavior
  - Protocol, successive ramps...
- Internal EOL pressure
  - FGs, He release
- Run beyond cladding breach
  - FP release, U dissemination...
- Iodine behavior
  - Release, role for SCC
  - Chemistry, link with other FP...

**Operational stake**

- Power plant maneuverability
- Fuel product life time
- Plant operation and maintenance, wastes
- Power plant flexibility, source term
From development process to experimental requests

Selection
- Irradiation global but precise monitoring (T, fission rate)
- Samples for PIE (microstructure analysis)

Characterization
- Numerous and robust on-line instrumentation
- Flexible LHGR time histories
- Intermediate NDE checking

Understanding
- Homogeneity and representativeness on several fuel rods
- Long term irradiations (creep, corrosion…)
- Conditioning before other tests (ramps…)

Qualification
- High LHGR
- Failure risk and radionuclide release management
- FP on-line measurements
- Damaged sample management

Safety tests
- Highly instrumented and automated test
- Devoted environment
- Phenomenology
Experimental requests - Example 1: Power Ramps

Stakes

- PCI limits (plant maneuverability, flexibility…)
- Kinetics effects - Ultra-fast ramp (up to 1000 W/cm.min)
- FP influence on clad behavior (I…)
- Fuel microstructure evolution (cracks, swelling, FP distribution….)
- Specific fuel vendor/utility needs

Experimental requests from the scientific team

- Welcoming power ramp system (various protocols, successive tests…)
- Ramp campaign: rod conditioning in another irradiation device
- Qualified power increase linearity control (automated system coupled with SPND results…)
- On-line measurement (clad elongation, FGR, coolant activity…)

- Reliable system
  - High accuracy on LHGR target
  - Strong experimental feedback
  - Results feed PCI modeling

- PIE support
Stakes

- Quantification of FGR margins versus limits
  - Release values + kinetics (Envelope power time histories, cycling…)
  - He release specific issue
  - Radioactive source term
- Reduction of uncertainties and margins (Tc, λ, LHGR…)
  - Non linear system: Slight Plin/T increase → Strong FGR increase
- Validation of advanced FG modeling

Experimental requests

- On-line FG measurement (gas sweeping) -> FP Laboratory
- Development of innovative in-pile instrumentation required
  - E.g. acoustic sensor (pressure + gas composition)
- Coupling with PIE thermal analyses
Hosting experimental systems for fuel samples under development

Moving box
to adjust easily the distance sample-JHR core

Δl=350 mm
V → ~5 mm/s
V back ~50 mm/s

For materials (Gen III, IV)
• CALIPSO (high performances)
• MICA

For LWR Fuels

- MADISON
  • Nominal conditions
  • Long term experiments
  • Comparative instrumented irradiation

- ADELINE
  • Beyond design criteria limits
  • High power, transients (power ramps…)
  • Post-failure behavior
  • FG sweeping and recovering

- LORELEI
  • LOCA tests on a separate effect approach
  • Thermal-mechanical behaviour of one LWR rod
  • Includes the post blow-down phase
The MADISON fuel experimental hosting system

**Description**
A loop device for irradiation of LWR fuel samples in normal conditions of power reactors
- In reflector
- On displacement system
- Heavy components in cubicle

**Type of experiment**
Characterization and qualification of fuel samples
- Fuel behaviour (FGR, µstructure evolution, corrosion…) vs BU and LHGR
- Long-term irradiations (fuel screening test or rod qualification)
- Re-irradiation before ramps

**Type of fuel sample**
All type of LWR fuel samples
- PWR / BWR fuel samples
- UO2 fuels (up to 7% in U5)
- MOX fuels (up to 15% Pu/(U+Pu))
- Fresh or high BU fuels (120GWj/t)
- Instrumented (CT, LVDT…)

**Carrying capacity**
Flexible loop with a large carrying capacity
- 4 rods clad diameter ≤ 10 mm
- 3 rods clad diameter ≥ 10 mm
- Possible evolution 7 rods 200W/cm

**Thermal hydraulics/Chemistry**
Representative of LWR power reactors
- PWR (155bars, 320 °C, 4 m/s)
- BWR (75 bars, T_sat, 1.8 m/s, low void fraction)
- Designed for 4 rods at 400 W/cm
- Standard chemistry (PWR /BWR)
- Specific chemistry (HWC,…)

**LHGR control**
Good homogeneity between any 2 identical fuel rods
- 3-5% max. heterogeneity (four fuel rods sample holder) for all type of fuels / Burn up
- Use of thin neutron screens
- Precise thermal balance

Design and manufacturing in collaboration with IFE-Halden
The ADELINE experimental hosting system

The ADELINE irradiation loop in the Jules Horowitz MTR: Testing a LWR fuel rod up to the limits with a high quality level experimental process

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The LORELEI hosting system

Objective
- Thermal-mechanical behaviour of one LWR rod
  - Ballooning and clad burst (fuel relocation)
  - Corrosion at high temperature
  - Quenching and post-quench behaviour
- Radiological consequences: FP source term (with/without fuel re-irradiation)

Technical design
- Device equipped with dewatering and quenching systems (gas and water tanks)
- Temperature controlled by displacement system
- Temperature distribution flattening: neutron screen (axial) and electrical heater (azimuthal)
- Quick installation (for short lived FP measurement) on END benches (gamma scanning and X radiography)
### A JHR hosting system development plan accorded to users needs

<table>
<thead>
<tr>
<th>System</th>
<th>Status</th>
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<tbody>
<tr>
<td>Madison (LWR fuel)</td>
<td>Available at the start of operation</td>
</tr>
<tr>
<td>Adeline (LWR fuel)</td>
<td>Available at the start of operation</td>
</tr>
<tr>
<td>Lorelei (LWR fuel)</td>
<td>Studied and Licensed</td>
</tr>
<tr>
<td>Instrumented capsule (fuel)</td>
<td>To be developed later on</td>
</tr>
<tr>
<td>Severe accident testing system (LWR fuel)</td>
<td>To be developed later on</td>
</tr>
<tr>
<td>Mica (material)</td>
<td>Available at the start of operation</td>
</tr>
<tr>
<td>Calipso (material)</td>
<td>Studied and licensed</td>
</tr>
<tr>
<td>Corrosion (material)</td>
<td>To be developed later on</td>
</tr>
<tr>
<td>SFR fuel testing systems</td>
<td>To be developed later on</td>
</tr>
<tr>
<td>GFR fuel testing systems</td>
<td>To be developed later on</td>
</tr>
</tbody>
</table>
Non Destructive Examinations in JHR:  
General objectives

- Initial checks of the experimental loading status just before the first irradiation  
  - Handling possible effects (transportation, insertion in the device)  
  - Precise positioning of instrumentation, sensors…

- Adjustment of the experimental protocol after a short irradiation run  
  - Sample behavior  
  - Power tuning…

- On the spot monitoring of the sample status after a test on the close-by stand located in the reactor pool  
  - Limited handlings to preserve the “as tested” sample geometry  
  - Geometrical changes after an off-normal transient  
  - Quantitative distribution of short half-life fission product…

- Final NDE tests after irradiation sequence  
  - On unloaded sample
Non Destructive Examination Benches in JHR

Underwater Neutron Imaging System
- Cracks and gaps
- Hydrides lenses
- Fuel or absorber composition

Fuel Hot cell: Gamma and XR scanning system & multipurpose test benches

Underwater photonic imaging systems (X-ray & $\gamma$) in reactor and storage pool

Feasibility study in progress with VTT collaboration

Sample examination
Phebus PF

Hosting system examination (fuel sample inside)

Density mapping
XR tomography (transmission)
Conclusions

-important work carried out on anticipation of users’ needs
  - As a key strategic input to steer priorities in hosting systems developments
  - As a key technical input for the development and the licensing
  - Necessary and beneficial for Users in order to get results as soon as possible

-JHR offers a wide experimental domain
  - A set of experimental hosting systems will be operational at the JHR operational starting
  - Development of some other systems closely linked to needs

-The JHR experimental capacity definition is also dependent from the existing Users community (JHR consortium, JHIP)

-International scientists (young fellows and/or senior experts) are welcomed within the JHR team for building the future JHR community