50 Years of Nuclear Fuel Qualification at SCK•CEN

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Nuclear Fuel Qualification - Definition

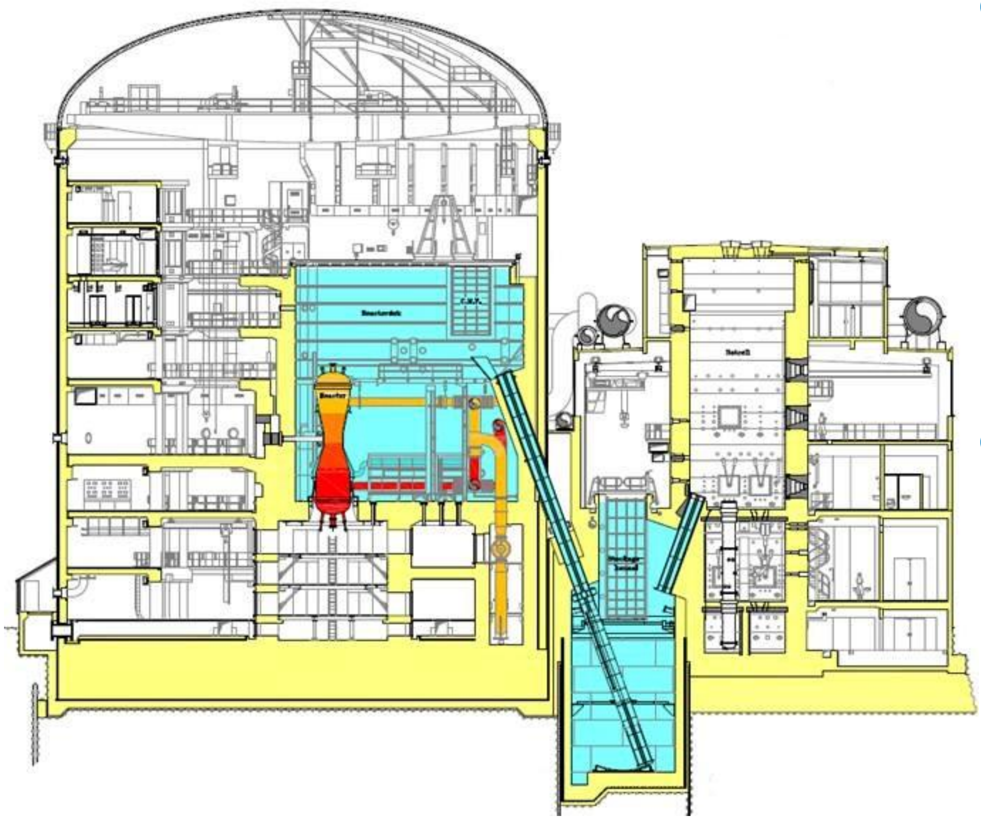
- prove that the nuclear fuel can accommodate the required fissions in full compliance with all duty and safety requirements
  - generate, conduct & give off the associated heat
  - while preserving the fuel component (rod/plate) integrity
  - in all anticipated service-life conditions
- based on descriptive / predictive code
  - of fuel performance
  - drawn up from and validated by
    experimental observations and theoretical considerations

Nuclear Fuel Qualification - Process

1. Exploratory phase towards a reference concept
   - from envisaged fuel duties & pre-existing knowledge/experience
   - narrowing down the material and design choice
2. Development of a fuel specification for a reference design
   - evaluation and improvement of (options within) the fuel concept
3. Feasibility of the licensing safety case for the reference design
   - generation of supportive data
4. Final qualification of the fuel for a specific application
   - generation of appropriate data-set (envelop, reproducibility, accuracy)
   - feed and validate the descriptive fuel performance code

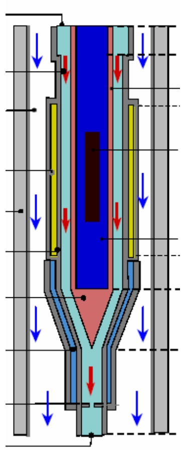
- SCK•CEN intensively engaged in all 4 phases with its
  - comprehensive set of experimental facilities (BR2 & LHMA & RCH)
  - theoritical / code developments on fuel performance

Research Reactor BR2 – general features

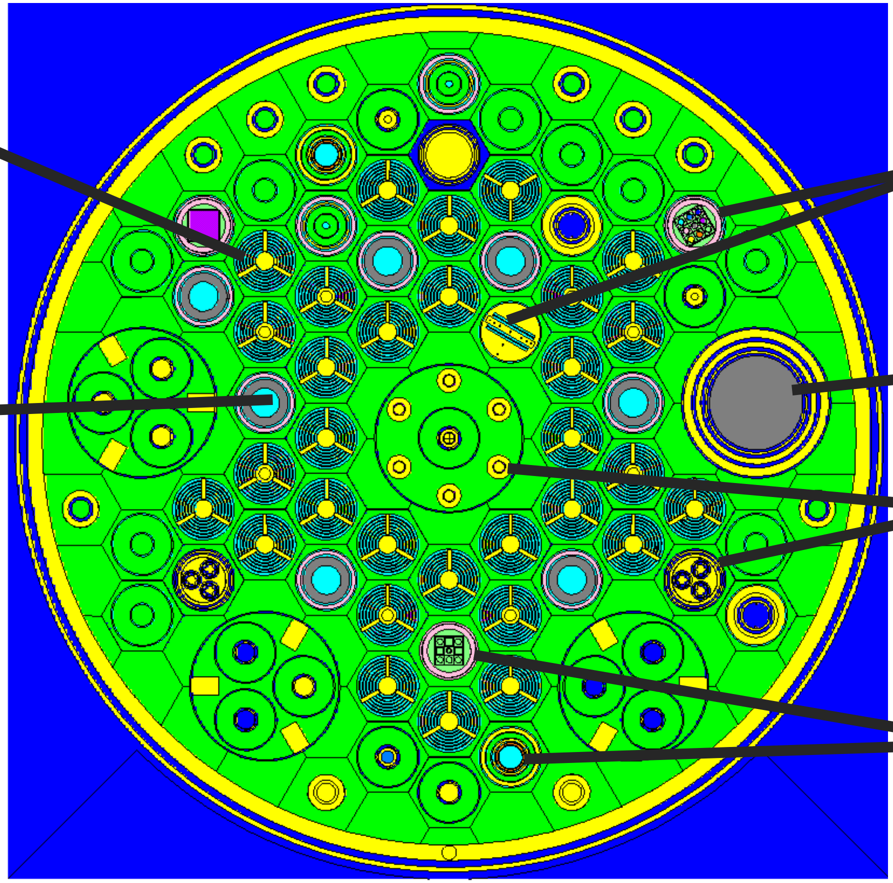


- Light water cooled tank-in-pool type reactor
  - primary circuit cooling capacity – design/nominal rating 100/60 MW
  - 1.2 MPa (5 bar) pressure, average temperature 40°C
- Pool connected to
  - water channel
  - hot-cell
  - ➢ allowing flexible (irradiated) material mounting and dismantling

BR2 = Multipurpose Reactor

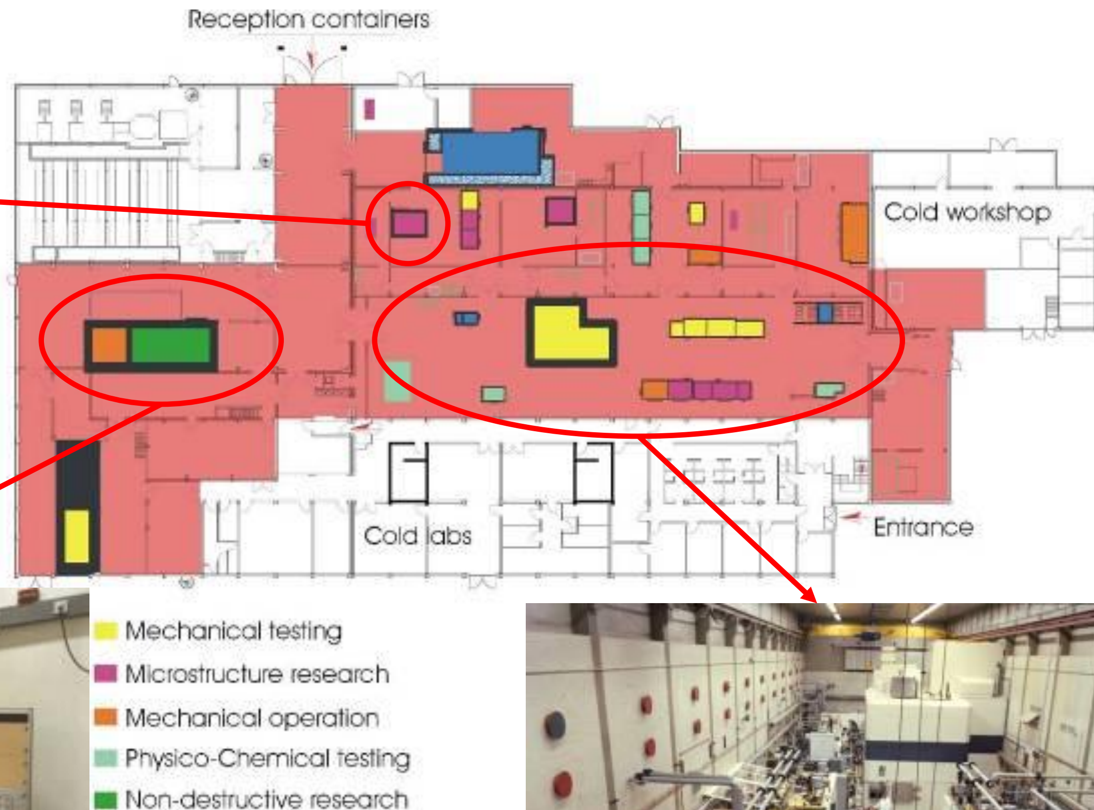


PWC/CCD Capsule
for transient testing fuel

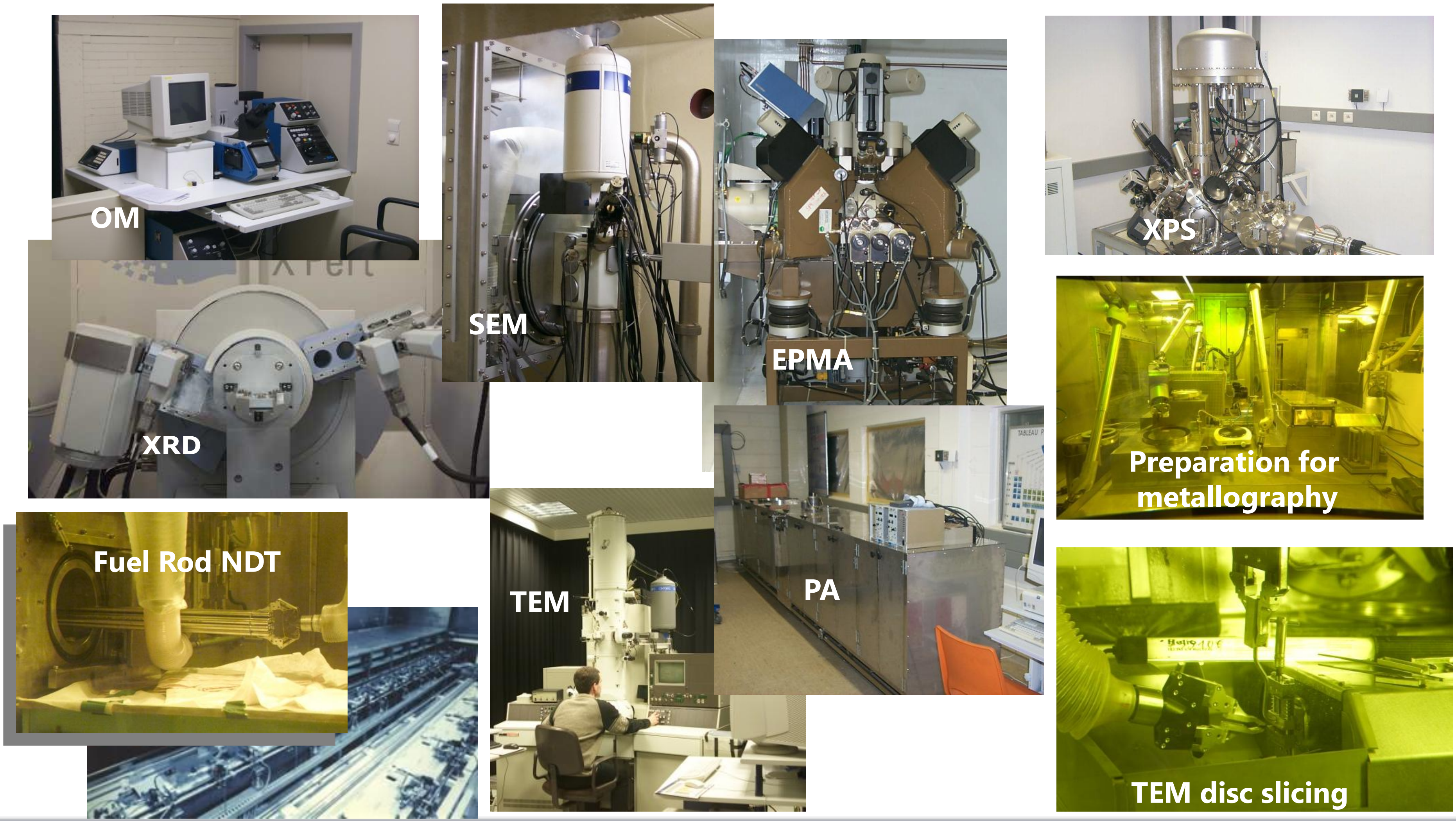


Mid-plane cross section of a typical BR2 core

LHMA – Laboratory for High and Medium Activity



Non-Destructive and μStructure Analysis Infrastructure



Hot Laboratories Nuclear Fuel Research Infrastructure

Base Irradiation
BR2/3 - NPP

Refabrication

BU extension
BR2 - CALLISTO

Transient test
BR2 - PWC/CCD

Non-destructive:

- Visual Inspection
- Clad Integrity
- Oxide thickness
- Rod length
- Profilometry
- X-ray Radiography
- Gamma Scanning
- Gamma Spectrometry
  ^{85}Kr
  ^{137}Cs
  ^{140}Ba/^{140}La ^{106}Ru

Destructive:

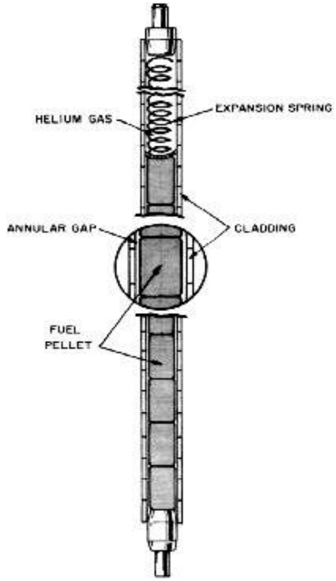
- Rod punction
- Mass spectrometry
- Fuel density
- Hydrogen content (clad)
- Optical Microscopy
- Autoradiography
- µ-hardness
- SEM
- EPMA
- XRD
- TEM
- XPS

Radiochemistry:

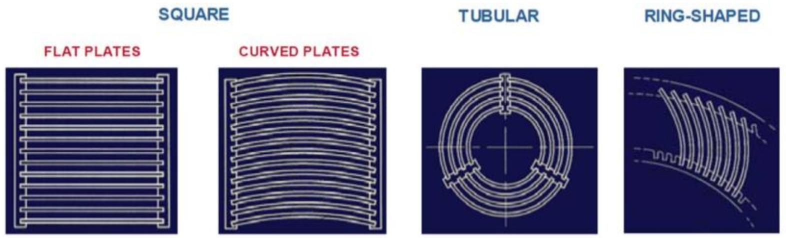
- Base actinides (U, Pu)
- Minor actinides (Np, Am, Cm)
- Fission products
  - Cs, I
  - Sr, Mo, Tc, Ru, Rh, Ag, Sb
  - Ce, Gd, Pm, Nd, Sm, Eu

Fuel Qualification Portfolio Extract

- LWR fuels
  - PWR & BWR and UO_2 and MOX (⇐ FR Fuel)
  - full-size NPP rods (base-irradiation)
    & RR rodlets (screening & transient testing)
  - driving forces = fuel performance prove with
    - better economy: cycle length ↗ - discharge BU ↗ - reactor power ↗
    - increased operation flexibility
    - appropriate (increased) reliability



- RR Fuel
  - uppermost n-flux ⇔ NPP = heat production
    - Fuel plates with high fissile material density in high heat conducting configuration



  - proliferation concerns: HEU (> 90 % ^{235}U) → LEU (< 20 % ^{235}U) conversion

LWR UO_2 Fuel Qualification Historic Milestones

- 1978-1990: HBEP (**H**igh **B**urnup **E**xperimental **P**rogram)
  - FGR study at high BU
    - 45 standard PWR/BWR rods from 3 fuel vendors
      - BU = 30 → 55 GWd/t_{HM}
      - 16 submitted to power-bumps to induce FGR onset
    - 37 parametric fuel rods from 6 fuel vendors (fill gas pressure, annular pellets, grain size)
      - irradiated in PWR/BWR 'pilot'-plants
      - BU = 50 – 70 GWd/t_{HM}
    - extensive PIE
  - Key results
    - first broad data-base for BU extension > 25-30 GWd/t_{HM}
    - identification of the rim-effect

LWR UO_2 Fuel Qualification Historic Milestones

- 1980-1990: TRIBULATION (**<u>T</u>**est **<u>R</u>**elated to H**<u>i</u>**gh **<u>Bu</u>**rnup **<u>L</u>**imitation **<u>A</u>**rising from **<u>T</u>**ransition **<u>I</u>**ncidents **<u>O</u>**ccuring **<u>N</u>**ormally in LWR's)
  - post-transitient fuel performance prove
    - 48 PWR fuel rods (17×17, UO_2, Zr4)
      - BU = up to 70 GWd/t_{HM} (>> 35 GWd/T_{HM} licensed)
      - ≠ clad production, UO_2 feed material, pellet design
    - BU accumulation in BR3 – transient in BR2 – further BU accumulation in BR3
    - extensive PIE after base & transient irradiation and at end-of-life
  - Key results
    - evidence, susceptibility & quantification of PCMI of ≠ fabrications
    - succes ~ separate effect tests for various design options in integral test
      - clad creep rate & rod growth ~ clad metallurgical state
      - pellet densification & swelling rate ~ production parameters
      - PCMI ~ rod design & fabrication paramters

LWR UO_2 Fuel Qualification Historic Milestones

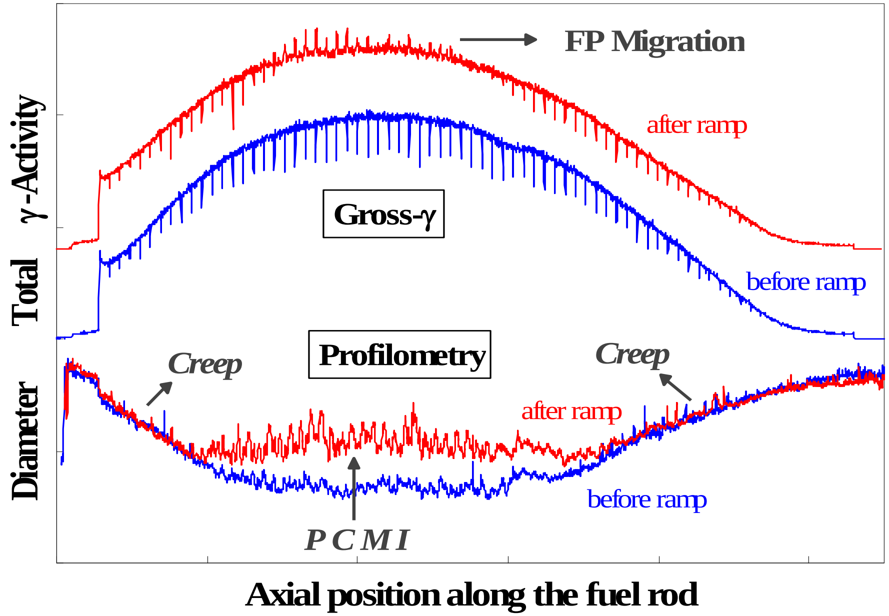
- 1983-1991: GAP (**<u>Ga</u>**dolinium de**<u>p</u>**letion) & GAIN (**<u>Ga</u>**dolinium **<u>In</u>**ternational Program)
  - study of performance of Gd_2O_3 doped fuel → cycle length & BU ↗ (PWR) & B_{BOC} ↘ (BWR) & reduce power peaking
  - GAP = neutronic study – assessment of Gd consumption
    - 5 Gd-doped fuel rods ([Gd] = 3-10%) + 18 standard UO_2 fuel rods
      - one cycle irradiation in BR3
      - PIE = radiochemical analysis & radial depletion profile Gd
    - Key results: reduce uncertainties & benchmark neutronic codes
  - GAIN = thermal-mechanical performance Gd-doped fuel
    - 26 Gd-doped fuel rods from 5 fuel vendors with various fabrication variants
      - Irradiated in BR3 to 10-72 GWd/t_{HM}
      - subsequent transient tests of 6 rods
      - PIE
    - Key results: assessment PCMI resistance of Gd-doped fuel (Gd_2O_3 ss in UO_2 ⇔ lower thermal conductivity, lower melting point, ≠ densification & swelling behaviour)

LWR MOX Fuel Qualification Historic Milestones

- 1986-2001: PRIMO (**<u>P</u>**WR **<u>R</u>**eference **<u>I</u>**rradiation of **<u>MO</u>**X Fuels)
  1987-1997: DOMO (**<u>Do</u>**dewaard **<u>M</u>**ixed **<u>O</u>**xide)
  - mechanical, thermal and neutronic properties of MOX
  - under representative PWR (PRIMO) & BWR (DOMO) irr. conditions
- PRIMO - 16 MOX rods from 3 fuel developers
  - two major fabrication variants: direct blending PuO_2/UO_2 & MIMAS proces
  - base irradiation (BR3 & Saint-Laurant) up to 20-60 GWd/t_{HM}
  - transient testing in BR2/OSIRIS/R2 $\rightarrow$ PCMI & FGR resistance testing
  - extensive PIE
- DOMO - 60 fuel rodlets assembled in 15 fuel rods (BN)
  - two major fabrication variants: co-milling co-precipitated $(U,Pu)O_2/UO_2$ & MIMAS
  - base irradiation (Dodewaard) up to 20-40-60 GWd/t_{HM}
  - transient testing in BR2 up to > 600 W/cm
  - extensive PIE at different stages of base irradiation & transient testing

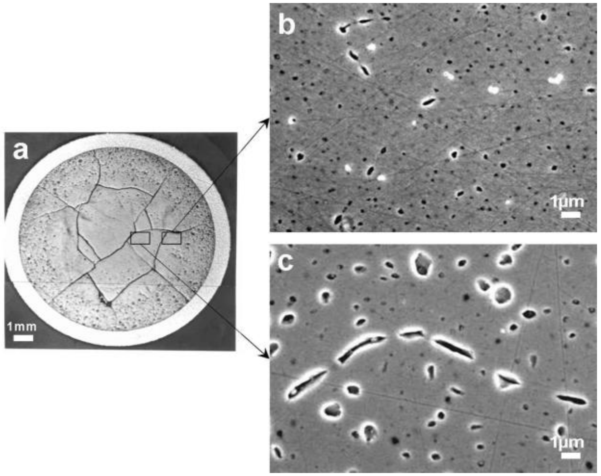
LWR MOX Fuel Qualification Historic Milestones

- Key results of PRIMO & DOMO
  - thermo-mechanical behaviour of MOX fuel quite similar to UO_2 fuel
  - excellent resistance of MOX fuel to PCMI
  - extensive license data-base
  - benchmark for neutronic codes for MOX assemblies



LWR MOX Fuel Qualification Historic Milestones

- 1997-2005: GERONIMO (**G**undremmingen **E**valuation & **R**esearch Program **O**n **Ni**ne by nine **MO**X BWR fuel)
  2000-2005: TOP-GUN (High Burnup Data on BWR 9×9 Fuel Rods Irradiated in **Gun**dremmingen)
  - Generate a complete validation data base for BWR-MOX 9×9
  - 12+4 full-size rods & 14 rodlets (MIMAS – 1-5% Pu_{fiss})
    - irradiated up to 50-80 GWd/t_{HM}
    - pool-side inspections (γ-scannings)
    - transient tests in BR2
    - extensive PIE

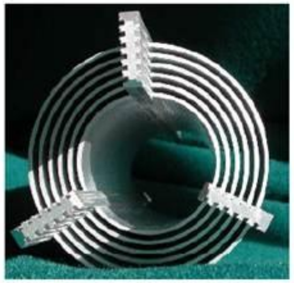


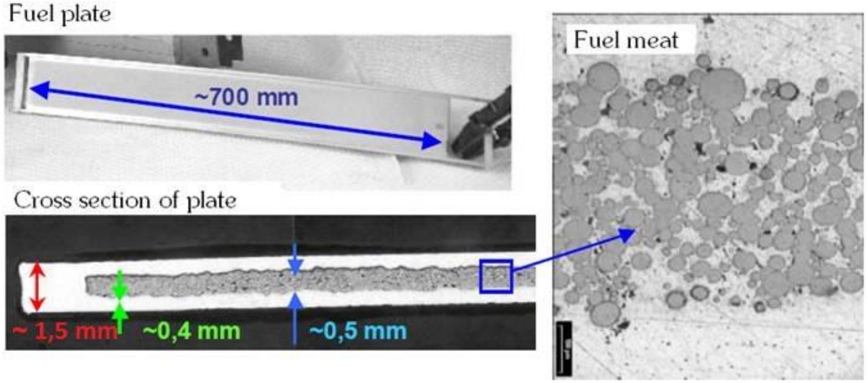
  - Key results:
    - extensive licensing data-base
    - no specific phenomena at very high BU
    - substantial higher release fraction of He ⇔ FG_{XeKr}
    - first measurements thermal conductivity MOX at ultra-high BU
      – thermal conductivity degradation less than extrapolated from lower BU

RR Fuel Development and Qualification

- Proliferation concerns ⇒ HEU (> 90 % ^{235}U) → LEU (< 20 % ^{235}U)
  - Research Reactor vs. Power Reactor fuel

Fuel element

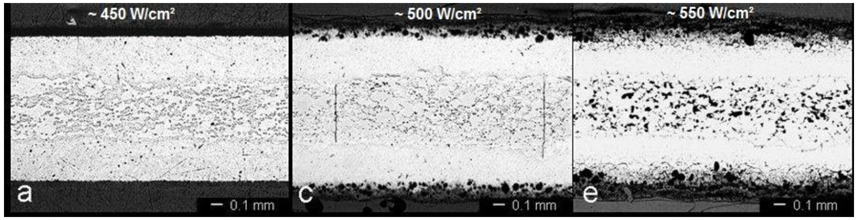




  - Conversion without severe losses in performance or increase in cost
    - 'Identical design': high fissile material density in high heat conducting environment
    - higher fuel density = fuel compound with more U-atoms/cm^3
      - UAl_x (4.3 g/cm^3) → U_3Si_2 (12 g/cm^3) → U-7w%Mo (16 g/cm^3)
    - higher fuel loading = more fuel per cm^3 fuel meat
  - Step-wise development & qualification
    - plate → mixed element → LTA

RR U_3Si_2 Fuel Development and Qualification

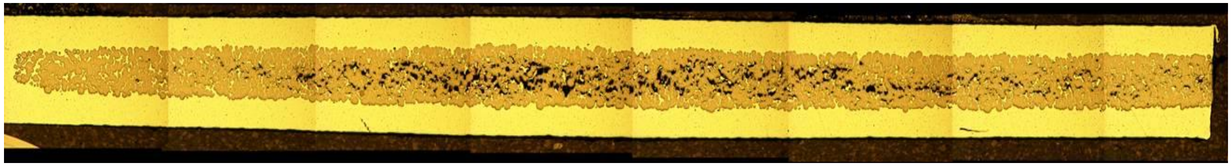
- 1988: 4,8 g U/cm³ U_3Si_2 fuel qualification (NUREG-1313/US-NRC)
  - low and medium power RR's qualification ⇔ high performance RR's adequacy ?
- Mixed elements with (higher) density U_3Si_2 dispersion fuel
  - 2002-2004: U_3Si_2 dispersion fuel at 5-6 g U/cm³ – key findings
    - outer clad degradation & FGR at BU of 25-29 at% (premature stop)
    - deficient clad corrosion resistance for anticipated operating conditions



    - off-normal beviour silicide fuel → no major issues related to steam ingress
  - 2006-2008: U_3Si_2 dispersion fuel with modified clad at 5 g U/cm³ – key findings
    - stable silicide fuel behaviour up to BU of 55-80 at.% (> 400 W/cm²)
    - extended and detailed PIE provided crucial data for feeding the modelling of fuel behaviour in dedicated computer codes
- EVITA (2009 - ...) – Enhanced Velocity Irradiation Test Apparatus
  - BR2 irradiation of RJH fuel element replicating JHR operating conditions
  - ongoing fuel design optimization & qualification

RR UMo Fuel Development and Qualification

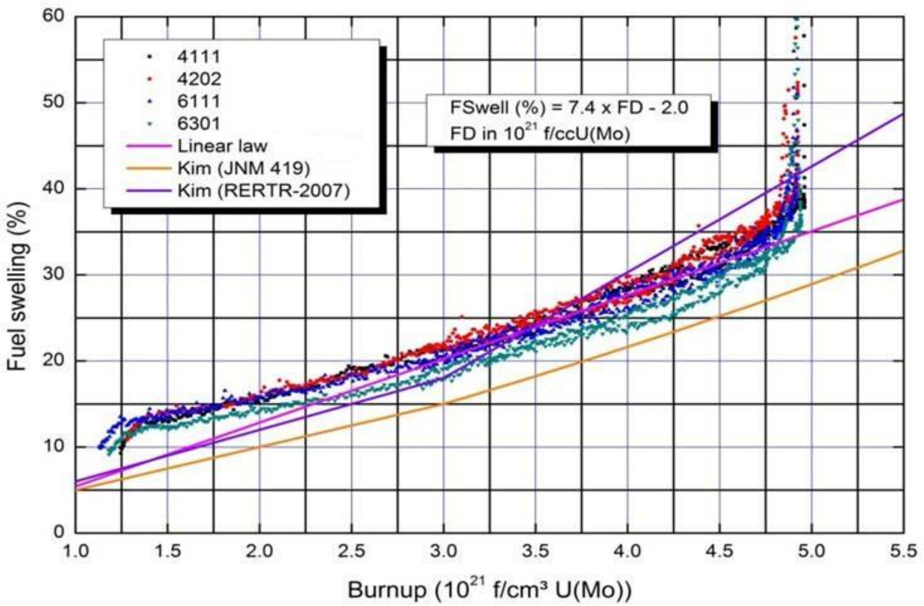
- 2002-2004: FUTURE (**Fu**el **T**est **U**tility for **Re**search Reactors)
  - high power irradiations & PIE of full-size UMo 7,5 g U/cm^3 dispersion fuel plates
  - key findings
    - pernicious swelling effects
    - route cause elucidated
      - ➢ formation of amorphous UMo-Al interaction layer inducing voids development



    - mitigation measure identified
      - ➢ Si suppression of the UMo-Al interaction ⇒ Si addition to Al or coating UMo
        - → supported by "old" but still functioning BR1 reactor fuel
          - U_{metal} slugs bounded to Al clad by Al-Si eutectic at fabrication (1950-ies)
          - its long term operation being a "long term diffusion experiment"
          - showing the effectiveness of Si for U-Al interaction suppression
          - confirmed by reaction activation energy measurements (U-Si > U-Al)
        - → confirmed by detailed PIE at SCK•CEN on French UMo-Al(Si) dispersion fuel plates
          - prove of beneficial effect of local Si presence at UMo-kernel/Al interface
          - appropriate Si "presence" & fabrication realization still to be elaborated

RR UMo Fuel Development and Qualification

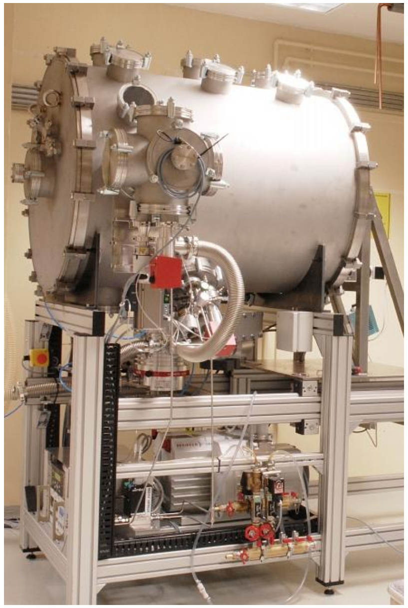
- 2006-2007: E- FUTURE (**E**uropean **FUTURE**)
  - 4 different UMo-Al(Si) 7,5 g U/cm^3 dispersion full-size plates
    - 4 & 6 % Si and different heat treatments (addressing appropriate Si position)
  - pillowing at higher BU → fuel swelling vs BU correlation



  - μ-structure PIE confirms IL formation associated with local low Si content
  - ➢ triggered SELENIUM R&D program at SCK•CEN

RR UMo Fuel Development and Qualification

- 2007-….: SELENIUM (**S**urface **E**ngineering of **L**ow **En**r**i**ched **U**-**M**o fuel)
  - design & construction of the barrel sputter coater (2009)
  - fabrication of coated UMo particles and plate fabrication (2010)
  - irradiation in BR2 (2011-2012)
  - ➢ NDT = no pillowing indications
  - ➢ DT PIE at LHMA (2013)
  - ➢ ….



- 2008-….: E-FUTURE 2
  - UMo-Al(Si) 7,5 g U/cm^3 dispersion full-size plates
    - 7 & 12 % Si and Al(Si) alloy (finer Si dispersion)

  ⇔plate buckling … at first or second irradiation cycle

Conclusion

- Three-decade timespan LWR fuel qualification research
  - concerned - huge fuel design variables in early days
    $\rightarrow$ to understand their effects
    - variable operation conditions later on
    $\rightarrow$ to extend operation regimes & improve reliability
  - large number of fuel rods $\Rightarrow$ statistically relevant licensing data-base
  - addressing almost unchanged major issues (FGR, swelling, PCMI, …)
  - within a comprehensive experimental setting
- RR fuel qualification
  - concerns higher U density plate configuration design development
    $\rightarrow$ for non-proliferation driven HEU-LEU conversion
  - restricted plate/element testing – enveloping conditions
  - addressing high fission density (FP accomodation)
    and high heat evacuation (dispersion stability/compatibility) issues
  - within an appropriate comprehensive experimental setting

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