Plans for Advanced Nuclear Fuels including ATFs in Switzerland and Related Management of Resulting Spent Nuclear Fuel

Stefano Caruso, NPP Gösgen

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Outline

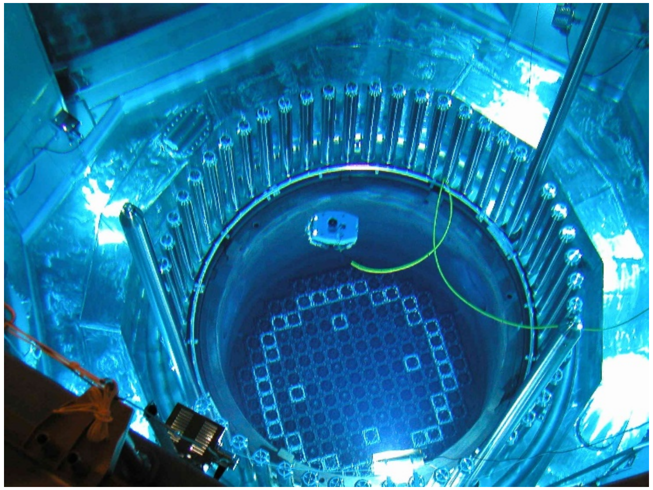
I. Gösgen Nuclear Power Plant (KKG)

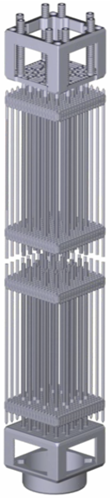
PWR, Siemens / KWU Design

- Single reactor with 1060 MWe (3002 MWth)
- Commissioned in 1979
- 3 loops plant

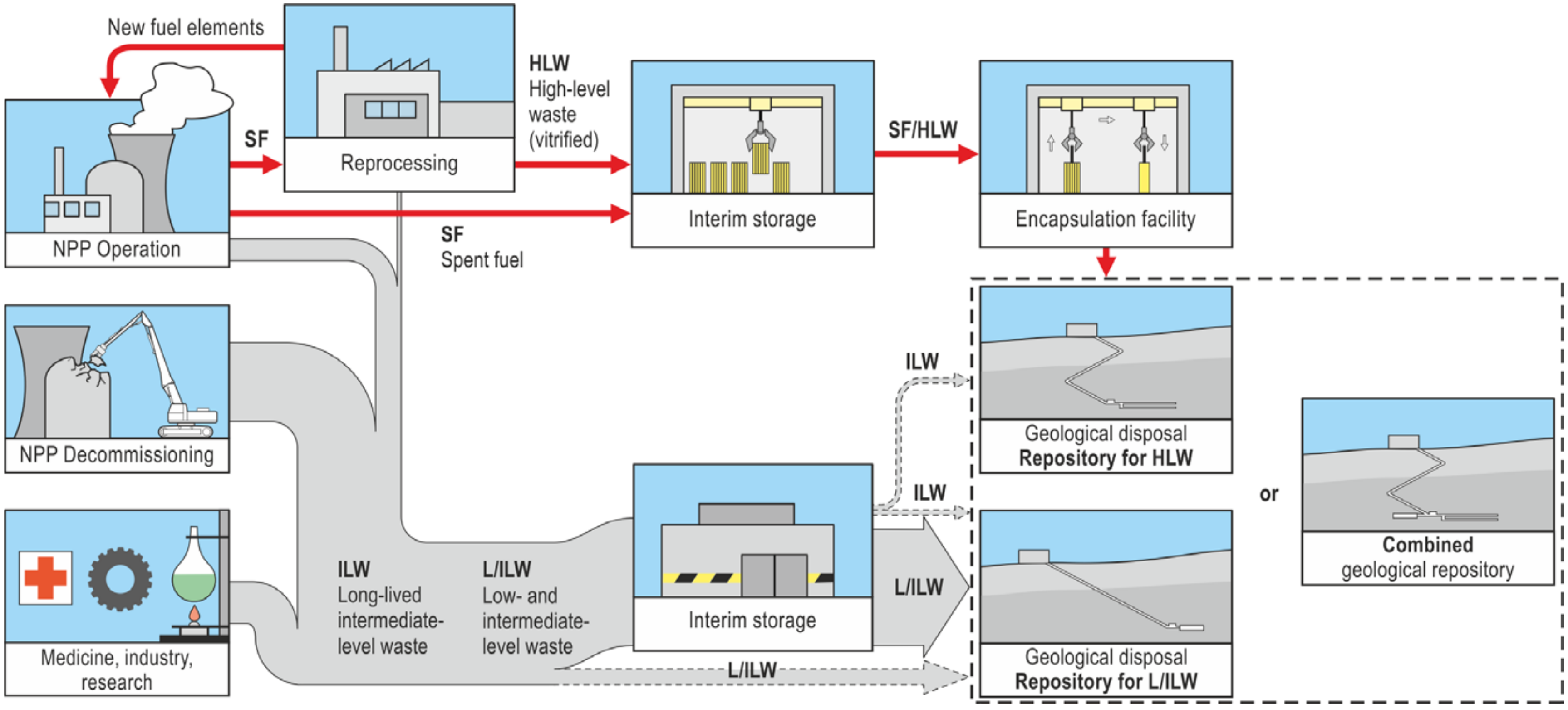
Fuel Key Features

- UO_2 4.95% (U and REP)
- 15X15 FA Design AREVA
- 177 FA in the core
- 205 Fuel Pins per Assembly
- 20 structural tubes per Assembly
- 5-zone core
- Low leakage loading pattern
- Max LHGR 525 W/cm
- Max FA-Burnup 70 MWd/kgHM



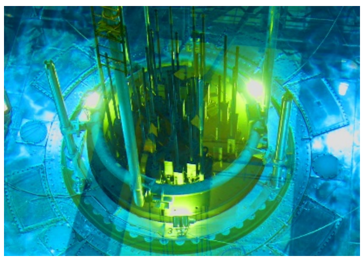


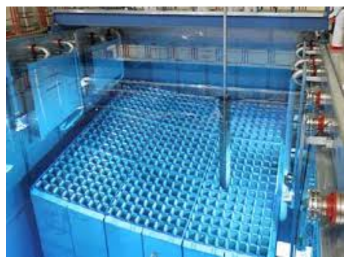
II. Spent fuel cycle in Switzerland



Back-end of Nuclear Fuel Cycle

- ✓ The safe, secure, reliable and economic management of spent fuel arising from nuclear power reactors is key for the sustainable utilization of nuclear energy


Reactor


Spent Fuel pool


Dry Interim Storage

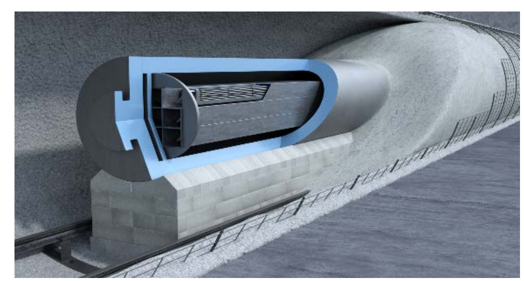

Cask Transportation


Nagra Surface Facility


SF unloading


SF loading


Canister welding


Final emplacement in geological repository

Back-end of Nuclear Fuel Cycle

✓ The safe, secure, reliable and economic management of spent fuel arising from nuclear power reactors is key for the sustainable utilization of nuclear energy

Operational Safety

Reactor

Spent Fuel pool

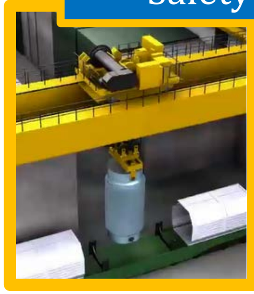
Ageing Management

Dry Interim Storage

Safety Assessment

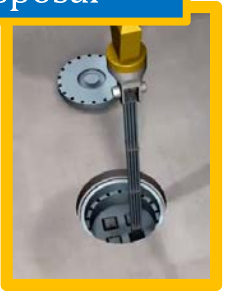
Cask Transportation

Safety Aspects of Pre-Disposal

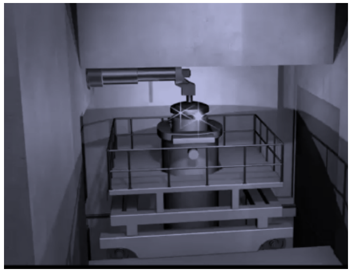


Nagra Surface Facility

SF unloading



SF loading



Canister welding

Long-term Safety

Final emplacement in geological repository

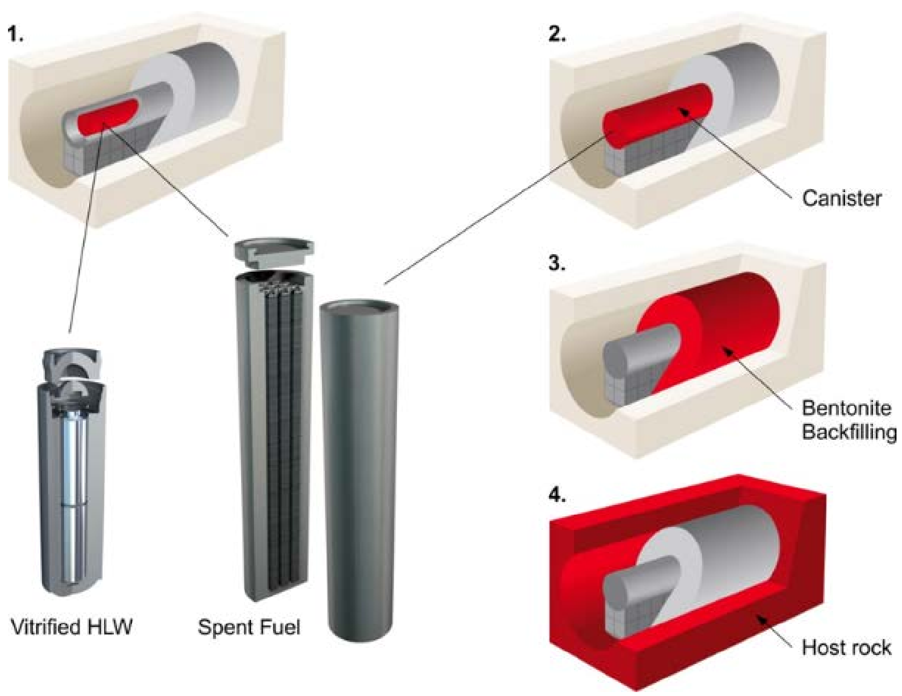
Swiss Interim Dry Storage Facility (ZWILAG)

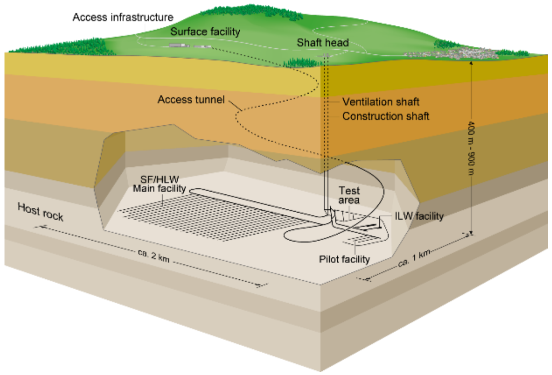
Centralized store located at Würenlingen:

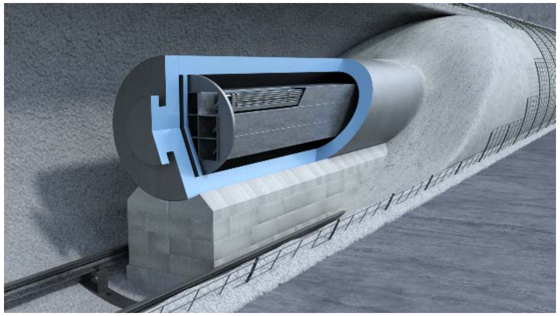
- in operation since 2001, designed to accommodate 200 transport and storage casks for vitrified HLW and spent fuel.
- E.g. TN97, TN52, TN24BH, TN81, TN9/4 (from Orano TN) and CASTOR V/19 & V/52, CASTOR geo32CH (from GNS)

III. Swiss Disposal Concept for Spent Nuclear Fuel (SNF)

- The SNF/HLW repository is expected to become operational by 2060 with emplacement until 2075. General licence application to be submitted by 2024 (Nagra)
- Safety concept based on **Multi-barrier system** in a stable environment







SNF characterisation for safety assessment

I. **Pre-disposal Operational Safety**: aspects are related to storage, transportation and encapsulation of the fuel at the surface facility
   - Radioprotection issues and radiological impacts (e. g. fuel assembly integrity and consequence of fuel release) -> influence to the encapsulation facility design

II. **Long-term Safety during disposal**
   - Safety analysis related to geological timescale, up to 10^6 years
   - Radiological impact on the near field and biosphere
     - Long term release of radionuclides inventory for large set of nuclides (two components)
       - 1) Fuel matrix ("slow" component); 2) cladding and structure material (relative "fast" component)
   - Criticality Safety Assessment with Burnup Credit application accounting for fuel and canister evolution
   - Decay heat -> impact to fuel loading strategies & total number of disposal canisters
     - Design Basis of 1.5 KW/canister (to preserve the multi-barriers properties)

IV. Fuel and Cladding integrity

- The Hydride Reorientation Story -

$Zr + 2H_2O \Rightarrow ZrO_2 + 4H+$

Zr-H binary system

I. Fraction of the hydrogen goes into solution in cladding when fuel is operated

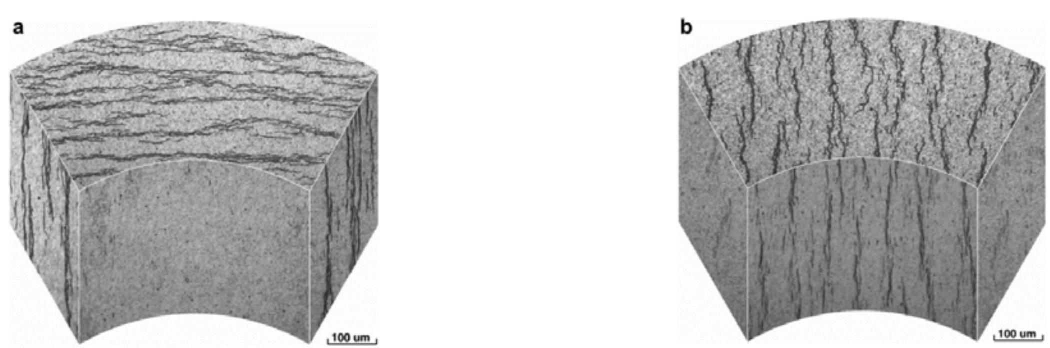
II. Hydrogen precipitates as hydrides when solubility limit is reached (higher concentration and/or lower temperature)

III. Usually, the orientation is **axial-circumferential** (a)

IV. Orientation is **axial-radial** (b) if a critical tensile stress level is exceeded

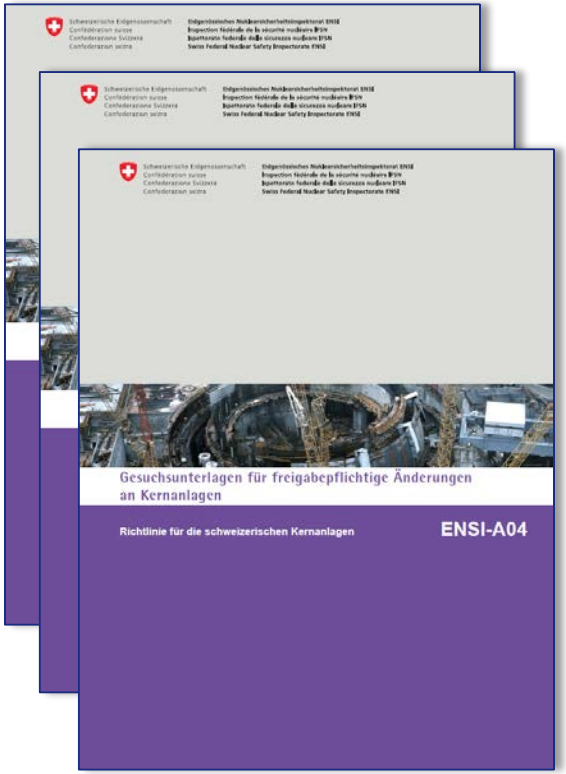
V. Mechanical properties of the cladding can be affected but at a higher stress level compared to hydride reorientation

Influencing factors: Temperature during storage, Internal rod pressure, Hydrogen concentration (therefore Burnup and **Cladding oxidation** as driving factors)



V. License Application Process for irradiation of nuclear fuel in Switzerland

- Irradiation of new fuel in reactor is subject to approval from the **competent authority** (**ENSI**)
- Applications for modifications to nuclear plants that are covered by existing operating licenses are dealt with by ENSI
- **Nuclear Energy Ordinance**: Safety Aspects part of the application are
  - Fuel element design
  - Core design (as changed by new fuel or mixed fuel core)
  - Definition of the safety limit values



V. License Application Process for irradiation of nuclear fuel in Switzerland

- Safety aspects are considering all phases of the fuel cycle:
  - Reactor, Storage and Transport, Pre-Disposal and Disposal
- Irradiation test campaigns and post irradiation examinations (PIE) are suitable steps in the license application for new types of fuel:
  1) Irradiation
  2) Pool Inspection and PIE, for the Evaluation of performance
  3) Approval from the authority or further requirements

Inspection and Repair Device at the KKG loading pool,

Responsibilities: Regulators and Implementers

Authority

- **KEG** – Kernenergiegesetz (Nuclear Energy Act), 03.2003 - **Federal Assembly of the Swiss Confederation**
- **KEV** – Kernenergieverordnung (Nuclear Energy Ordinance), 12.2004 – **Federal Council**
- **UVEK** - Department of the Environment, Transport, Energy and Communications / **BfE –** Swiss Federal Office of Energy
- **ENSI** - Swiss federal nuclear safety inspectorate (Regulator)

Implementers

- **NPPs** – Nuclear Power Plants, Direct operation of reactors and dry/wet storage facilities on site.
- **ZWILAG** – Centralised dry storage facility –
- **Nagra** – Company responsible for the geological disposal of Swiss waste

Spent fuels remain under responsibility of the NPPs until final emplacement in repository

Relevant documents for the licensing process

- **KEG** – Kernenergiegesetz (Nuclear Energy Act)
- **KEV** – Kernenergieverordnung (Nuclear Energy Ordinance)
- **UVEK -** Federal Department of the Environment, Transport, Energy and Communications – *Regulation for Protection Against Incidents in Nuclear Installations*
- **Swiss federal nuclear safety inspectorate (ENSI)** Guidelines:
  - ENSI A04 regarding changes to fuel assemblies and control rods, changes to safety criteria, changes to validation methods, spent fuel disposability
  - ENSI A03 regarding operational experience and related relevance to the periodic safety checks (PSÜ)
  - ENSI G20 regarding qualification of programs, calculation methods, validation and quality for reactor core, fuel assemblies and control rods
  - ENSI G03 regarding geological repository
  - ENSI guide to ageing management during dry storage

Fuel testing at Gösgen helps licensing of new fuel

Sample
- Sample's irradiation
- Pool inspection + PIEs
- Authority's Approval for next phase

LTR
- LTR (Lead Test Rod) irradiation
- Pool inspection + PIEs
- Authority's Approval for next phase

LTA

ENSI Requirement

- LTA (Lead Test Assembly) irradiation
- Pool inspection + PIEs
- Final Approval from Authority for Core Loading

- **KKG operational safety is not affected by availability of advanced fuel**
- **No benefit to the current KKG safety criteria is to be addressed by the program**

VI. Advanced Nuclear Fuel - Accident Tolerant Fuel (ATF)

- Main objective of **ATF** is to increase coping time during beyond-design basis accidents that means improved high temperature oxidation
- Benefit to Spent Fuel Management can be also considered as a secondary effect

Specific to Spent Fuel Management:

- It aims to reduce hydrogen/corrosion reaction with water. This will increase the cladding/fuel integrity with respect to the back-end operations
  - Reduction of hoop stress by reducing indirectly fission gas release (reducing corrosion, it improves the heat conductivity on the cladding)
  - Less hydrogen reduces the risk of several well-known degradation mechanisms like hydride reorientation

VI. Advanced Nuclear Fuel - Accident Tolerant Fuel (ATF)

Main approaches to enhanced LWR fuels:

- **Cladding coating** (short-term solution): To deposit coatings on Zr alloys: oxidation-resistant surface layer (Cr). This is applies to existing cladding types.
- **Alternative cladding** (long-term solution): Use alternative cladding materials, like ceramics (SiC composites or Fe-based alloys) instead of conventional Zr alloys (FeCrAl, SiC_f/SiC)
- **New Fuel**: Use of doped UO_2 fuel (Cr_2O_3-doped, Al_2O_3-doped) and/or use of advanced fuel (microcell UO_2 pellet)

N.B.: This list is general (not Gösgen and Framatome specific) not intended to be comprehensive of all types of advanced materials currently under research and development

Advanced Fuel: Framatome-Gösgen collaboration

Enhanced Accident Tolerant Fuel (EATF) & others

I. Near-term evolutionary solution:
   - Cr-coating on M5 (not properly EATF)
   - Cr_2O_3-doped UO_2 fuel with M5 and/or Duplex

II. Long-term revolutionary solution:
   - Silicon carbide composite (SiC_f/SiC) cladding

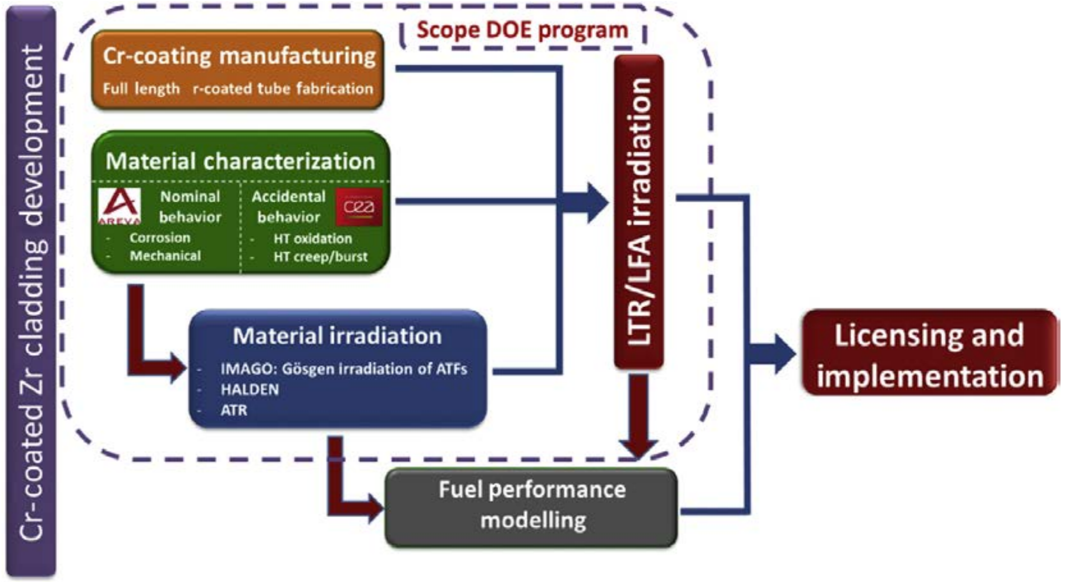
The chrome coating is applied to the cladding tube by means of PVD (Physical Vapour Deposition)

Coating Properties

1. Reduced high temperature oxidation
2. Reduced corrosion
3. Improved wear resistance

VII. R&D Activities and Testing programs

- Collaboration Framatome / KKG, several programs running
- Two-Stages program: **Irradiation** + **Post Irradiation Examination**
- Phase 1. R&D-Program 2016 - 2023: **IMAGO**
- Phase 2. R&D-Program 2019 - 2026: **GOCHROM**



***Reference**: Bischoff et others, AREVA NP's enhanced accident-tolerant fuel developments: Focus on Cr-coated M5 cladding, Nuclear Engineering and Technology 50 (2018) 223-228*

Post Irradiation Examination (PIE) in Gösgen pool and at Paul Scherrer Institute (PSI)

- Evaluation of the Operational Behaviour
  - Annual pool-Inspections at KKG
- Rod removal after the 1st 3rd and 5th cycle
- PIE-Targets of PIEs:
  - Visual Inspection
  - Gamma Scanning
  - Metallographic Investigation
  - Measurement of Hydrogen pick-up

IMAGO Program

IMAGO (**I**rradiation of **M**aterials for **A**ccident-tolerant fuels in the **Go**esgen reactor)

- First Irradiation of Cr-coating in a commercial PWR
- **Objectives**: is to verify the behavior of EATF concepts in representative PWR conditions:
  - Assessment of the coating's integrity with irradiation
  - Corrosion behavior under irradiation
  - Microstructural evolution under irradiation (& some mechanical properties)
- **Material tested**: Cr-coated zirconium alloy and SiC/SiC composite cladding samples – just clad !

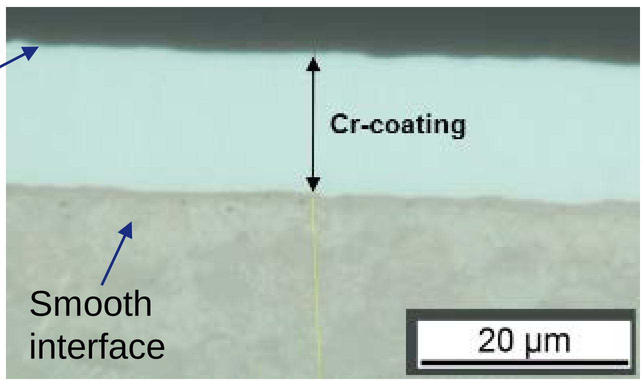
- **Irradiation phase**: Cr-clad samples placed within the guide tubes of some fuel assemblies, in contact with the coolant (up to **7 irradiation cycles**)
- **Post irradiation examinations**: Samples have been already investigated (one and two irradiation cycles) at the hot cell of the research institute PSI.

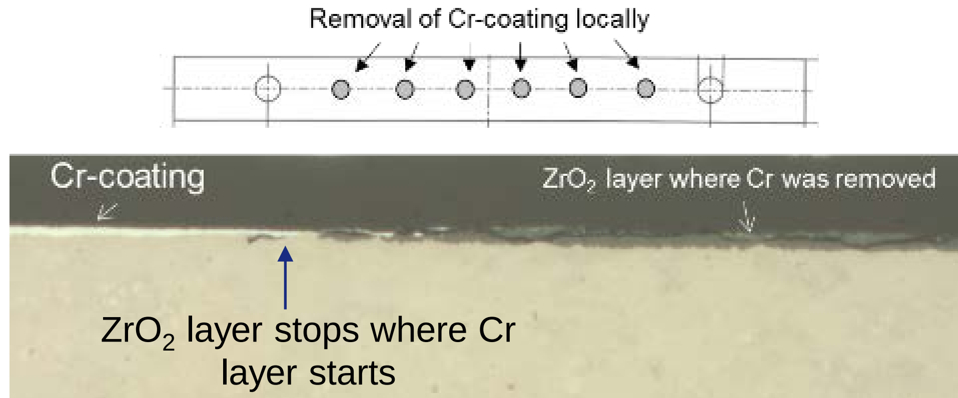
IMAGO-2016: First results from hotcell examination at PSI

- **Cr-coated** samples irradiated in the Gösgen reactor for 1 cycle

Cr-coated sample	Pre-damaged samples

No observable Cr_2O_3 oxide





- Metallographic analysis confirms out-of-pile observations: good stability of the coating + very low corrosion kinetics under irradiation

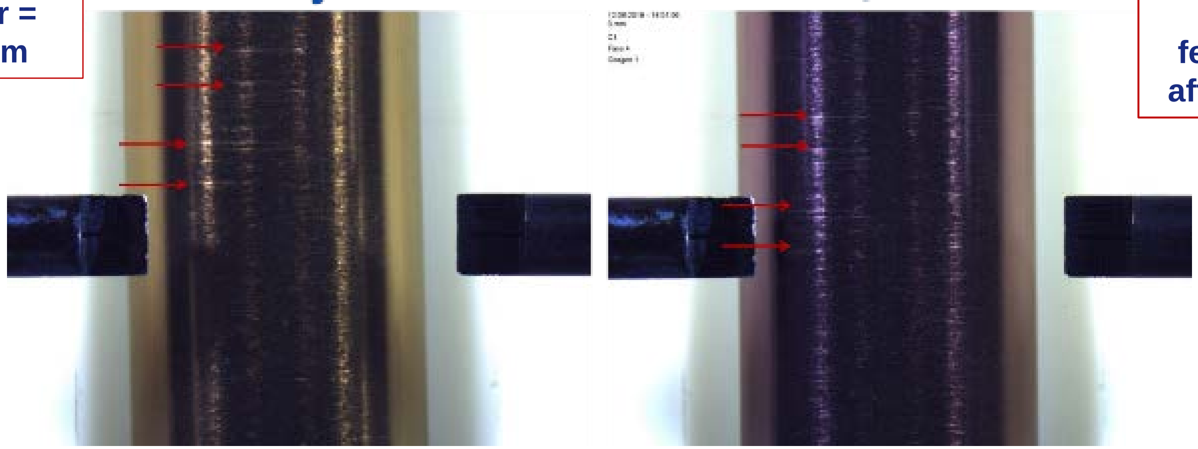
Reference: *Duquesne et al., Feedback from the irradiation of PROtect's Cr-coated M5Framatome cladding in the Gösgen commercial reactor, NuMat 2020*

IMAGO-2016 : Visual Examination after 3 cycles

- Visual inspection performed with a color HD camera that allows the comparison of small features after 2 and 3 cycles:

Reflective color = thickness < 1µm

2 cycles | **3 cycles**



Same surface features observed after 2 and 3 cycles

- Excellent irradiation behavior of Cr-coated cladding
- No defects, delamination or other degradation of Cr-coating layer

Reference: *Duquesne et al., Feedback from the irradiation of PROtect's Cr-coated M5Framatome cladding in the Gösgen commercial reactor, NuMat 2020*

GOCHROM Program

Program details

- Follow-up of IMAGO
- Insertion of 20 Cr-coated M5 full-length fuel rods in two different fuel assembly (LTR: Lead Test Rod) in KKG
- Fuel: UO_2 and doped UO_2
- Two irradiation cycles completed
- The design criteria of the GOCHROM fuel rod design are unchanged. Thermo-mechanical compatibility with the existent fuel in reactor

Objective

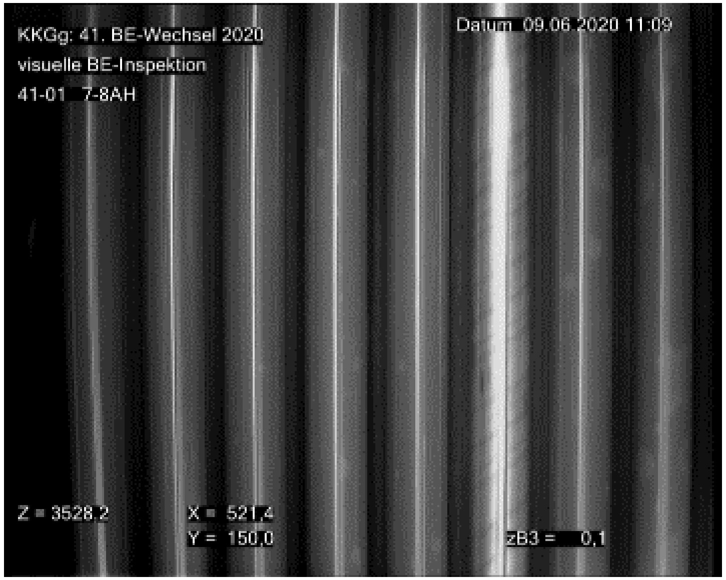
- Operating behavior of the chrome-coated fuel rods

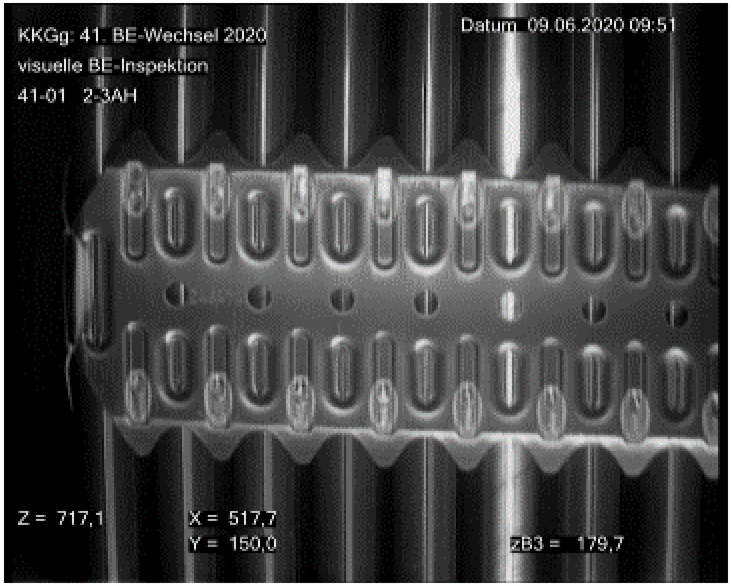
Target / Benefit

- Lower oxidation rate during accidents (LOCA)
- Hard protective layer (minimizing debris fretting)

GOCHROM Program – First Results

Visual inspection AFTER **one cycle** of irradiation in Gösgen





***Reference**: Duquesne et al., Feedback from the irrad. .., NuMat 2020*

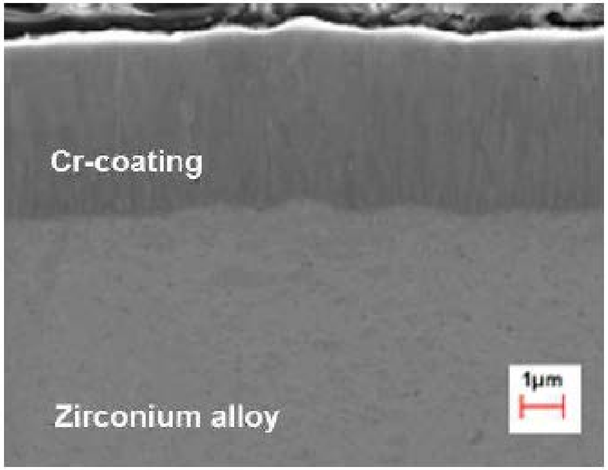
Cr-coated M5

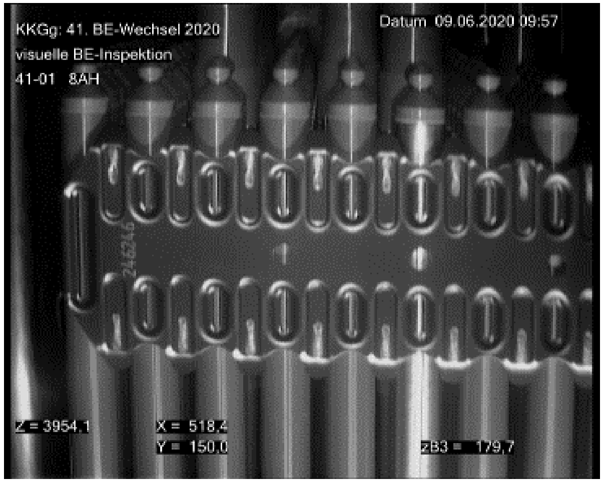
Cr-coated M5

- All inspected rods show a bright metallic appearance
- No indications for corrosion in visual inspections (confirmation of IMAGO results)

Preliminary analysis from the Framatome/ Gösgen Program outcome

- The chrome coating is very stable.
- The interface between Cr and Zr shows a high degree of homogeneity and no porosity. As expected, a stable thin oxide layer (passivation) forms on the chromium.
- The Cr-M5 fuel rod is significantly less oxidized than the pure M5 fuel rod.
- The expansion of the cladding tube and the bursting did not result in any flaking of the chrome coating.





Joint programs and collaborations with other countries

KKG is taking part directly or indirectly to several international activities for the evaluation of the SNF performances:

- **R&D activities** together with Paul Scherrer Institute, JRC Karlsruhe, Framatome and Westinghouse
- OECD/NEA-Studsvik **SCIP IV (Studsvik Cladding Integrity Project)**: Task 1 is devoted to long-term storage. Testing of ATF material under accidental conditions is also planned. KKG indirect participation with ENSI and Swiss NPPs
- Joint program between KKG, Nagra and Framatome on long term aging behavior of FA structural components by simulation of the aging process during dry storage
- Observers in EURATOM Project "**EURAD-SFC**: Spent Fuel Characterization and Evolution"

VIII. Role of the fuel/cladding integrity at Back-End

- **Cladding integrity** **as safety criterion** for the **pre-disposal operations**
  - SNF transportation

    Radiological impact, Criticality safety
  - SNF cask unload, handling and final encapsulation

    Radiological impact (release on the environment)

- **Cladding integrity** **not a safety criterion** **after emplacement**
  - Multi-barriers concept based on

    Canister (Steel, Steel + Cupper) / **Buffer material** (Bentonite) / **Rock** (Opalinus Clay)

VIII. Role of the fuel/cladding integrity at Back-End

But, for long term **Criticality Safety Assessment** (CSA) in repository:

- Time frame of one million years
- Potential evolutionary scenario: collapse of a canister after 10’000 -100’000 years (depends from boundary conditions and country specific approach).
- Cladding & fuel geometrical changes are considered too. Collapse of fragments after cladding break-up seems more likely
- Cladding and fuel dissolution and reconfiguration are improbable events.
- However, this is part of the safety assessment and it may bring to much higher Burnup-Credit requirements
- **Possible benefit of ATF**: new cladding types with corrosion resistance may contribute to redefine the boundary conditions and release, to some extend, the safety requirements on CSA

Acknowledgments

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- Dr. **Elmar Schweitzer**, Framatome GmbH, Coordinator in-pile testing of AFT fuel at Framatome

Thank you for the attention!