DE LA RECHERCHE À L'INDUSTRIE

# In-core Instrumentation for MTR Experiments


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# Summary

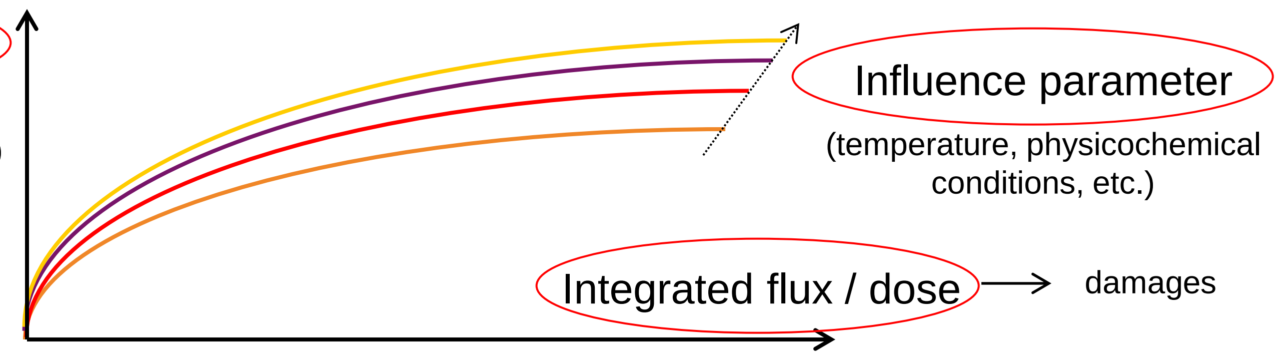
# 1. General requirements

# Illustration of measurement needs for material testing

In-core measurements are essential to:

- **Monitor the experiments**

**Objectives of irradiation tests :**
**Assess / verify / increase the precision of behavior laws under irradiation**




→ All these parameters must be accurately measured !

- **Watch safety parameters**

= check that some specified parameters stay in their acceptable range
(e.g. : temperature, pressure, etc.)

# 1. General requirements

## Main stakes for in-core instrumentation

*Radiation measurements*

**Reduction of uncertainties in experimental conditions**
- Neutrons / gamma flux
- Neutron spectrum
- Neutron dose

**Better knowledge of nuclear heating**
→ design of experimental devices

*Physical parameter measurements*

**Better characterization of thermo-hydraulic conditions**
→ temperature field / fluid flows

**Highly instrumented experiments**
« Cook and look » → Online measurement of experimental parameters

**Material behavior**
New materials, better representativeness
- Temperature
- Deformations (creep…)

**Fuel improvement and qualification**
- Fission gas release
- Pellet-cladding interaction
- Accidental conditions (LOCA)

# Main reactor measurement needs and R&D programs

- **Reactor measurement needs**
  - **Radiation measurements**
    - Neutron flux
    - Nuclear heating
    - Fluence / dosimetry
    - Nuclear data
  - **Measurement of physical parameters**
    - **Measurements on material and fuel samples**
      - Temperature
      - Deformation
      - Mechanical loading
      - Defects, failure
      - Fission gas release
      - Thermal conductivity
      - Corrosion thickness
    - **Measurements on environment**
      - Fluid temperature
      - Fluid pressure
      - Physical-chemistry
      - Mass flow
      - Diphasic flow, void fraction

# 1. General requirements

## Ways to develop and qualify in-core instrumentation are changing

**Tomorrow:**

Extended field of validation

Advanced signal analysis

**Today:**

Physician approach

Development and qualification of instrumentation modeling

Improvement in related nuclear data

**Yesterday:**

Engineering approach

Mainly empirical characterization

Limited field of validation

## 2. Conditions of measurement

- a. Physicochemical environment
- b. Effects of radiations
- c. Operational issues

## Physicochemical environment of in-core instrumentation

### High temperature:

→ LWR conditions : 300-400°C continuous (up to 1200-1800°C in transients)
→ SFR conditions : 400-500°C continuous
→ HTR-VHTR conditions, materials for fusion : 800-1200°C continuous

### Various media:

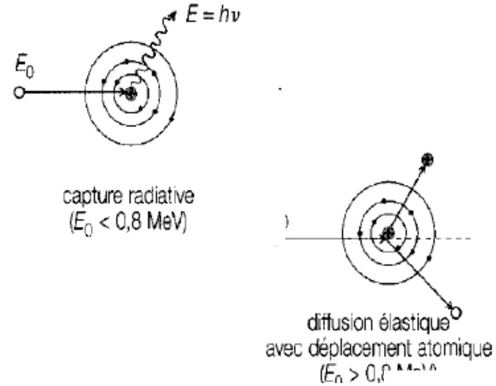
→ Pressurized water (+ bore and lithium)
→ Liquid metals (NaK, Na…)
→ High-temperature gas

*Typical alloys used for in-core components*

| Type | C | Cr | Fe | Mn | Mo | Ni | Si | Zr | Others |
|---|---|---|---|---|---|---|---|---|---|
| **Stainless steels** | | | | | | | | | |
| AISI 304 L | 0,03 | 18 à 20 | reste | 2 | | 8 à 12 | 1 | | |
| AISI 316 L | 0,03 | 16 à 18 | reste | 2 | 2 à 3 | 10 à 14 | 1 | | |
| **Nickel alloys (Inconel)** | | | | | | | | | |
| Alloy 600 | 0,05 | 14 à 17 | 6-10 | 1 | | > 72 | 0,5 | | Co < 0,1 |
| Alloy 718 | 0,08 | 17 à 21 | reste | 0,35 | 2,8 à 3,3 | 50 à 55 | 0,35 | | |
| **Zirconium alloys** | | | | | | | | | |
| Zircaloy 4 | | 0,1 | 0,2 | | | | | reste | Sn = 15 |
| Zr-Nb | | | | | | | | reste | Nb = 1 - O = 0,12 |

## Main effects of nuclear radiations on sensors

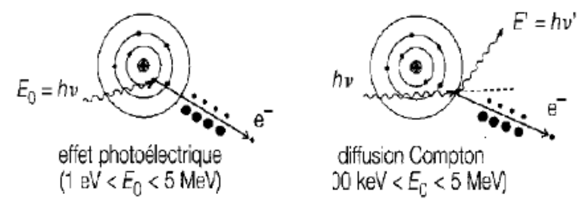
→ **transmutations** : composition changes




→ **damages :**

- alteration of electric insulators
- wires breaking
- change in mechanical properties

→ **noise current** (Compton and photoelectric effects)




→ **heating**

→ Precautions :

- choice of materials
  - form (metals, oxides, ceramics…)
  - elements → nuclear properties
- remove sensor from high-radiation areas when possible
- in-situ calibration

# Effects of transmutation on in-core sensors

Due to neutron capture $\,^{A}_{Z}X + \,^{1}_{0}n \rightarrow \,^{A+1}_{Z}X' + \gamma \rightarrow \,^{A+1}_{Z+1}Y + \,^{0}_{-1}\beta^{-}$

the material X disappears under irradiation : $N(t) = N_0 \, e^{-\sigma\phi t}$

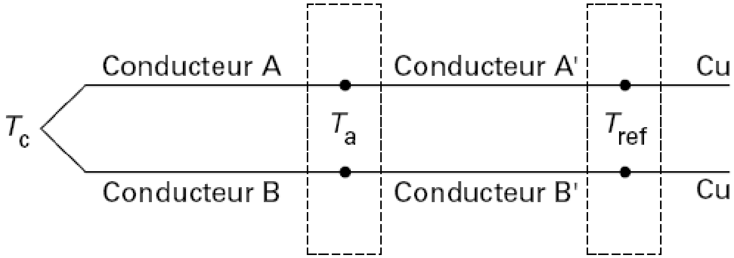



Illustration : effect on thermocouples

Change in wire composition

→ change in thermoelectric response

= drift of the signal

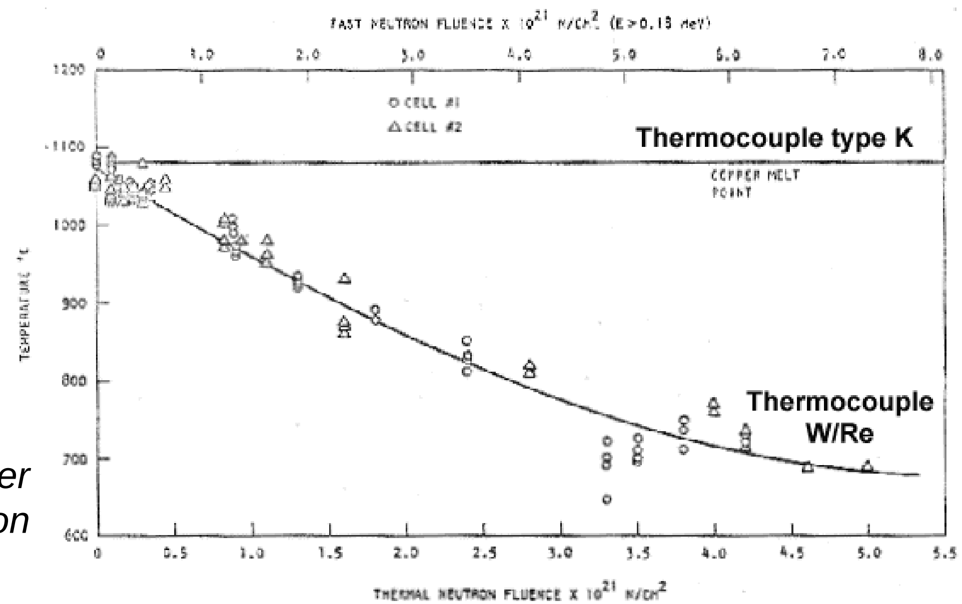
| Materials of standard thermo-elements | Si | Al | Cr | Mo | Ni | Pt | Mg | W | Re | Rh | Ir |
|---|---|---|---|---|---|---|---|---|---|---|---|
| σ (barn) neutron cross-section of the main isotope | 0,08 | 0,23 | 0,73 | 2,5 | 4,2 | 10 | 13,5 | 19,2 | 86 | 150 | 460 |

# Effects of transmutation on in-core sensors

Illustration : effect on thermocouples

Important effect on high-temperature thermocouples (W/Re, Pt/Rd…)

**W** → Re + Os (σ = 19 barn)
**Re** → Os (σ = 86 barn)
**Rh** → Pd (σ = 146 barn)




*Drift of thermocouple signal under MTR irradiation*

| Type of thermocouple | Drift in MTR due to irradiation |
|---|---|
| **K** (Ni-Cr / Ni-Al) | **Not significant** |
| **C** (W-Re5% / W-Re26%) | **-1°C / 2.10$^{19}$ n/cm$^2$** (-0,9 °C / day) |
| **S** (Pt-Rh10% / Pt) | **-1°C / 1,4.10$^{19}$ n/cm$^2$** (-1,2 °C / day) |

# 2. Conditions of measurement
# c. Operational issues

## Operational issues

**High reliability** (impossible maintenance on irradiated sensors)

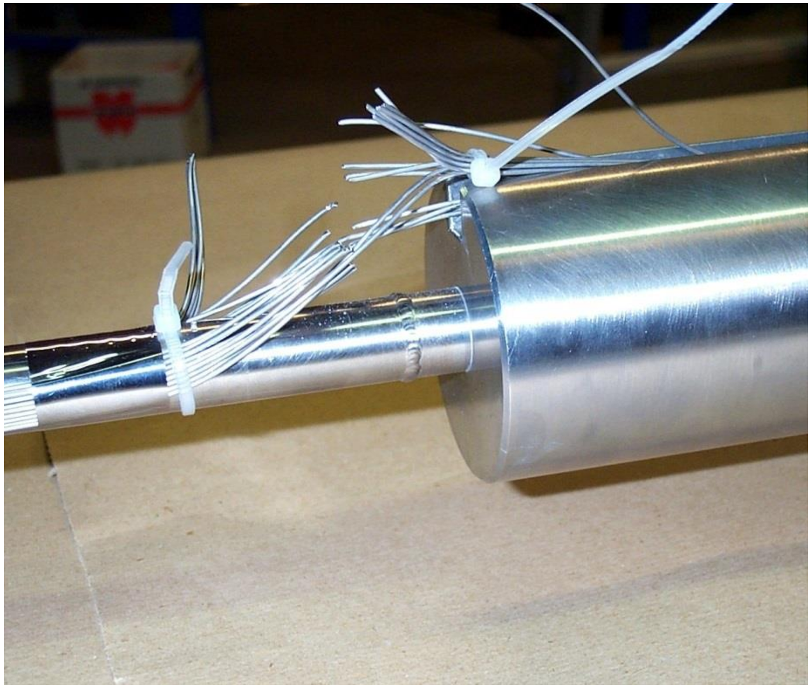
**High accuracy** (higher scientific requirements. Example : in-core deformations must be measured with ~ µm accuracy)

**Miniaturization** (very narrow experimental devices : a few millimeters available for instrumentation)

Large distance between sensor and electronics (tens of meters)

## Operational issues

### Fragile instrumentation in difficult conditions of implementation



Damaged cables

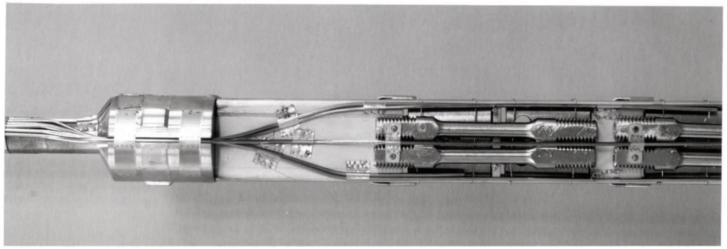
Repairing a mineral insulated cable

# 2. Conditions of measurement

## Summary of in-core measurement conditions

- **High accuracy required** to meet scientific and technical needs
- **High constraints** related to reactor conditions:
  - constraints due to irradiation (high neutron and gamma flux: material damages, composition changes, parasitic signal, etc.),
  - constraints due to physicochemical conditions in experiments (high temperature, pressurized water, liquid metals, etc.),
  - constraints due to integration (miniaturized sensors because of small size devices, long distance between sensors and electronics, etc.),
  - constraints due to operation (high reliability requirements because of difficult or impossible maintenance or replacement of irradiated instrumentation).

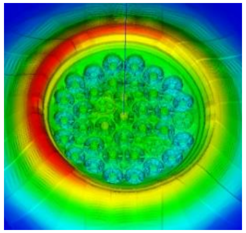
**Innovation** is necessary !

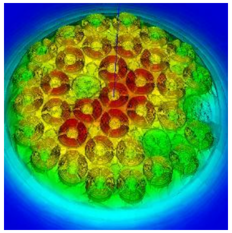


# 3. Examples of in-core instrumentation

## 3.1. Neutron and gamma flux

# Neutron and gamma measurements





## Objectives :

**To measure and reduce the uncertainties on:**

- Thermal and fast neutron flux
- Gamma flux and nuclear heating

## State-of-the-art :

**Neutron flux:**

- Activation foil dosimeters and wires (post-irradiation analysis) + Unfolding techniques
- Fission chambers for thermal and fast neutron
- Self Powered Neutron Detectors

**Gamma flux:**

- Ionization chamber
- Self Powered Gamma Detector (with Bi emitter)

**Nuclear heating:**

- Calorimeter (Gamma Thermometer and Differential Calorimeter)

## Developments :

- **Simulation tools for FC and SPND signal**
- Dosimetry for epithermal flux

# 3. Examples of in-core instrumentation
# 3.1. Neutron and gamma flux

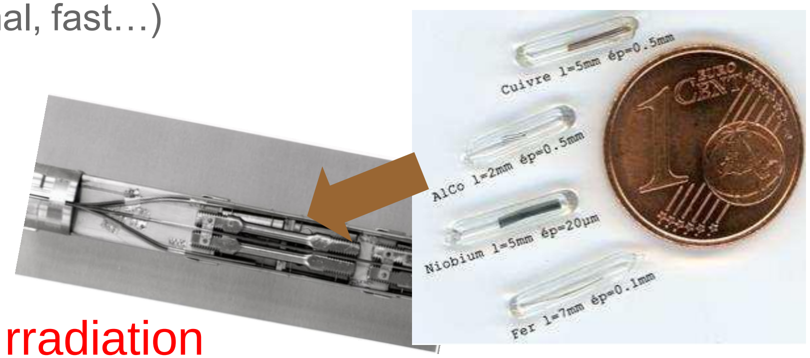
## Activation dosimetry

= measurement of the radioactive activity of an irradiated material sample (dosimeter)

- Reference measurement for neutron flux and fluence
- High accuracy
- Selection of the neutron energy domain (thermal, epithermal, fast…)

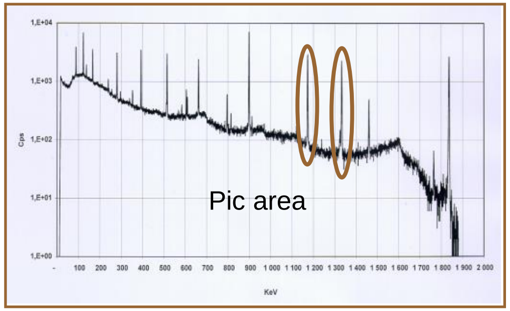
But post-irradiation analysis (no online measurement)

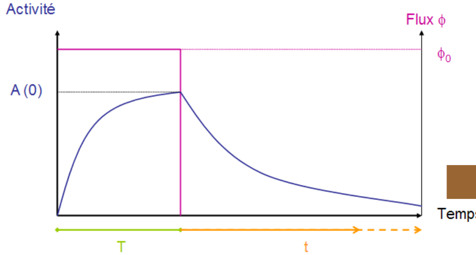
*Dosimeters*




Irradiation → Transportation

Activity measurement (spectrometry γ or X)




Irradiation history
geometry model

Cross section

Activity

**Reaction rate, fluence…**

$$A(t) = \Phi_0 \,.\, N_1 \,.\, \sigma_1 \,.\, (1- e^{-\lambda.T}) \,.\, e^{-\lambda.t}$$

# Activation dosimetry

## Short-life materials for dosimeters

| Dosimeter | Au197 | 59Co | 55Mn | 115In | 103Rh | 115In |
|---|---|---|---|---|---|---|
| Reaction | n,γ | n,γ | n,γ | n,γ | n,n' | n,n' |
| Daughter | 198Au | 60 Co | 56Mn | 116m In | 103 m Rh | 115m In |
| T | 2,6944 days | 5,271 years | 2,57878 hours | 54,20 minutes | 56.1 minutes | 4.486 hours |
| Spectrum energy area covered (MeV) | th+ épi | th + épi | th + épi | th + épi | E > 0,7 | E > 1,3 |

| Dosimeter | 58Ni | 64Zn | 54Fe | 24Mg | 27Al | 51V |
|---|---|---|---|---|---|---|
| Reaction | n,p | n,p | n,p | n,p | n,α | n,α |
| Daughter | 58C0 | 64Cu | 54Mn | 24Na | 24Na | 48Sc |
| T | 70.82 days | 12,701 hours | 312,13 days | 14,9574 hours | 14,9574 hours | 43.67 hours |
| Spectrum energy area covered (MeV) | E > 2,7 | E > 2,8 | E > 3 | E > 6,1 | E > 7,3 | E > 11 |

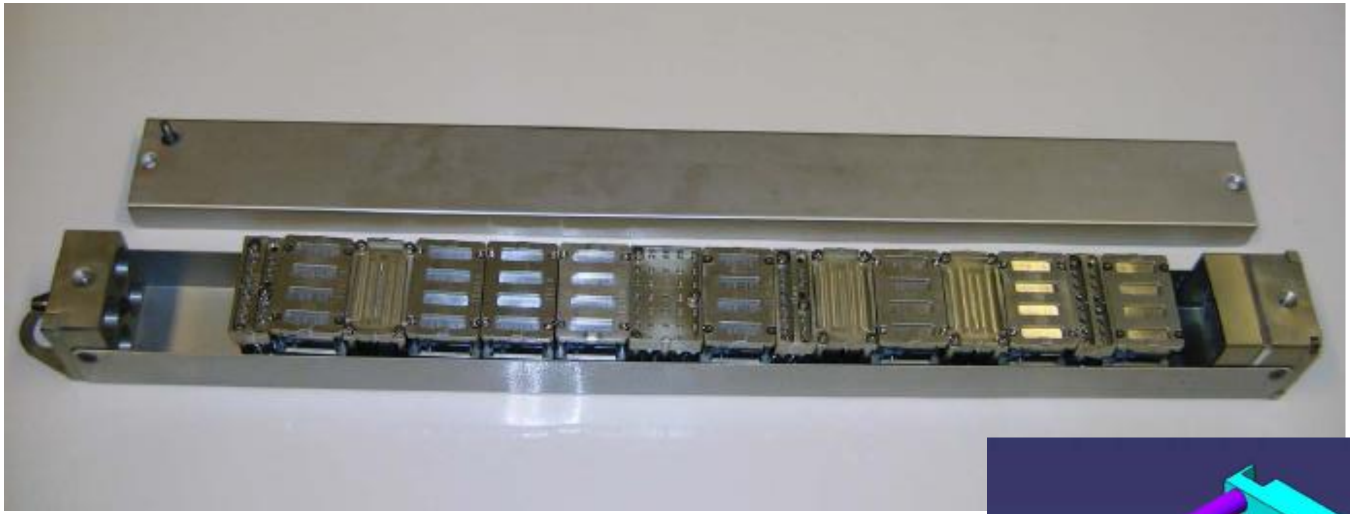
# Activation dosimetry

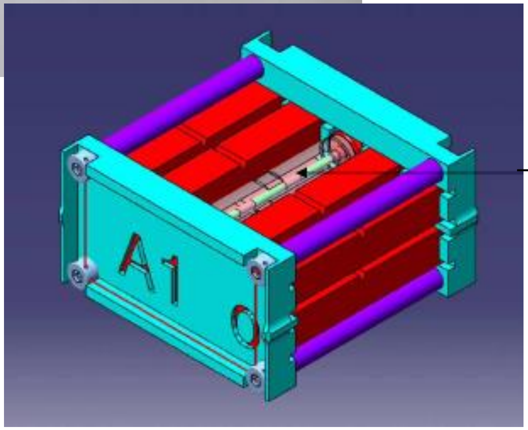
Long-life materials for dosimeters

| Isotope (Number) | shape | Container | Réaction | Effective Threshold (MeV) | Measured radio-isotope | Decay period |
|---|---|---|---|---|---|---|
| Cobalt (3) | Al-0,5%Co Wire ∅ 1,0 mm | | $^{59}Co(n,\gamma)$ | Thermal +Epithermal | $^{60}Co$ | 5,27 y |
| Cobalt (3) | id.(b) | | $^{59}Co(n,\gamma)$ | Epithermal | id. | 5.27 y |
| $^{237}$Neptunium (1) | $NpO_2$ + MgO | Cd filter Ti box | $^{237}Np(n,f)$ | 0,6 MeV | $^{137}Cs$ | 30 y |
| $^{238}$Uranium (1) | Powder $U_3O_8$ | Cd filter Ti box | $^{238}U(n,f)$ | 1,5 MeV | $^{137}Cs$ | 30 y |
| Ni (3) | Wire ∅ 1,3 mm | | $^{58}Ni(n,p)$ | 2,8 MeV | $^{58}Co$ | 70,8 d |
| Fe (3) | Wire ∅ 1,0 mm | | $^{54}Fe(n,p)$ | 3,1MeV | $^{54}Mn$ | 313 d |
| Cu (3) | Wire ∅ 0,8 mm | | $^{63}Cu(n,\alpha)$ | 6,8 MeV | $^{60}Co$ | 5,27 y |

# Activation dosimetry

Illustration of dosimeter implementation : neutron fluence monitoring for material testing experiments

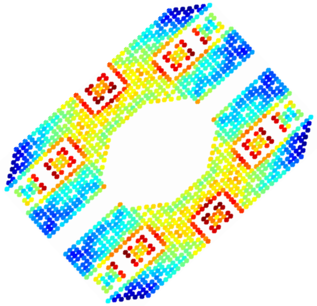


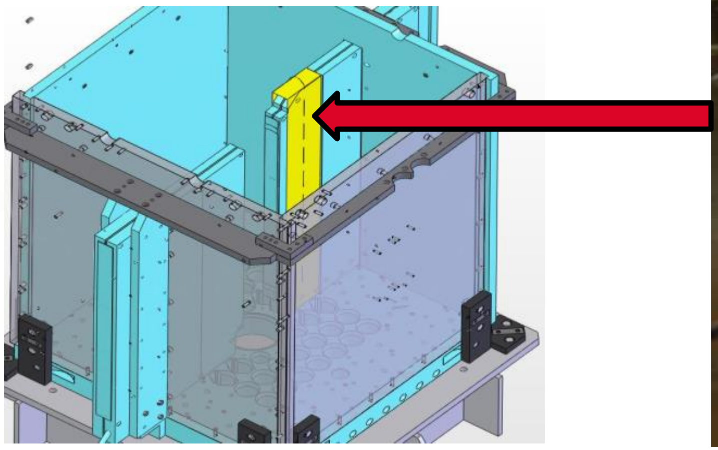


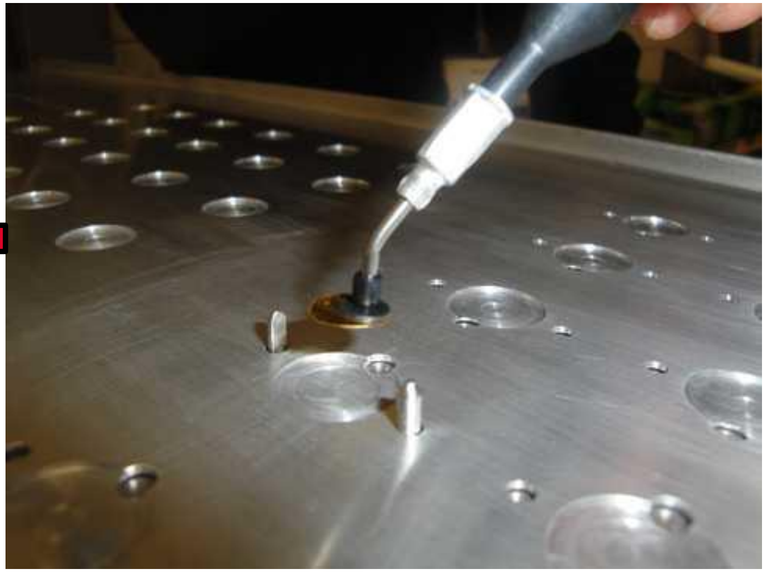

**Dosimeter location**

# Activation dosimetry

Illustration of dosimeter implementation : flux mapping







# Activation dosimetry

## Illustration of measurement facility : MADERE Platform at CEA Cadarache

Performs reactor dosimetry measurements for research reactors and for the Surveillance Program of French PWRs

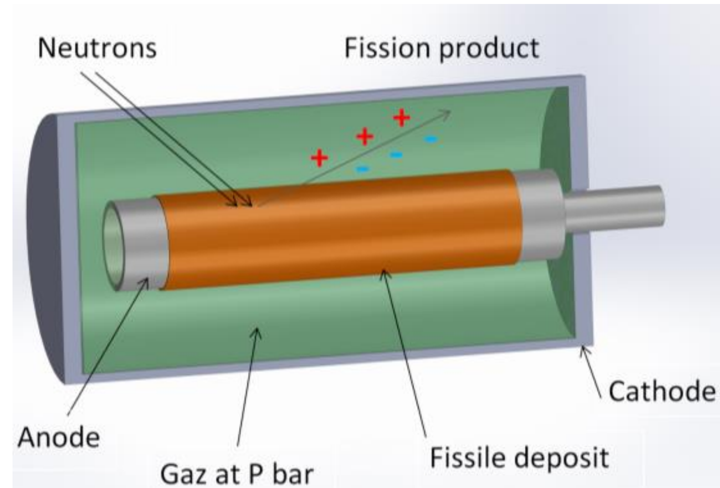
→ Measurement of $\gamma$ and X activity of solid samples

→ Range : 0.1 Bq to $10^8$ Bq / dosimeter

→ Uncertainties : 1% à 5% (k=1)

# Fission chambers

Measurement of the current generated by fission reactions in a fissile material deposited on an electrode




An effective detector for measuring neutron flux

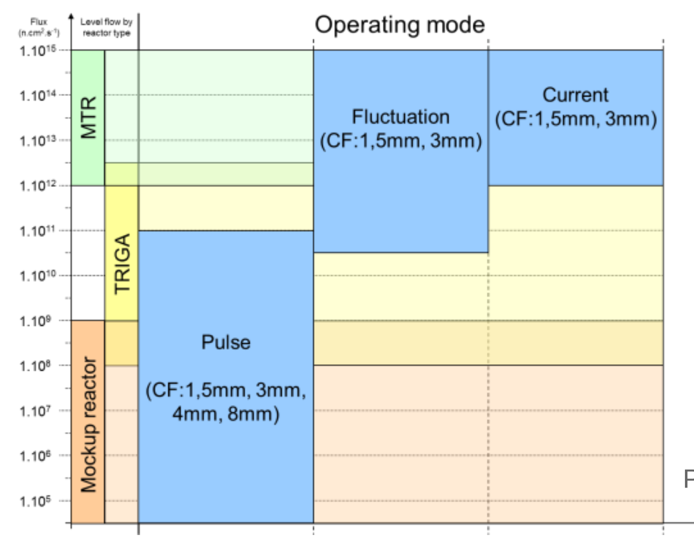
- High linearity signal (10 decades)
- Real-time online measurement

A modular detector

- Choice of fissile isotope and mass deposit
- Adaptation of technological parameters:
  geometry, nature and pressure of gas...

A multi-information signal

- Three operating modes depending on flux range
- Neutron / gamma effective discrimination

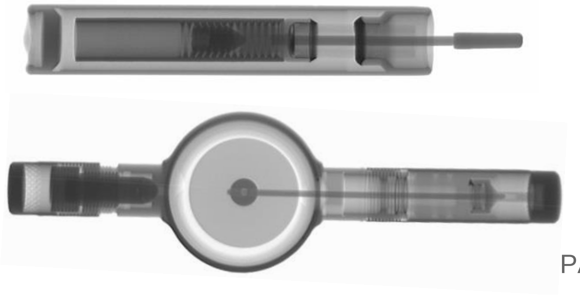


# Fission chambers

## Fission chamber manufacturing workshop at CEA Cadarache

→ Manufacturing specific fission chambers with various possible fissile deposits (mass/composition) : U, Pu, Th, Np, Am, Cm… and specific designs

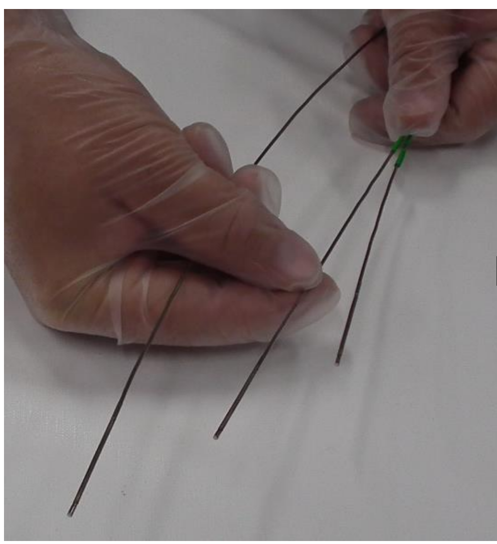
→ Imagery and controls (RX)



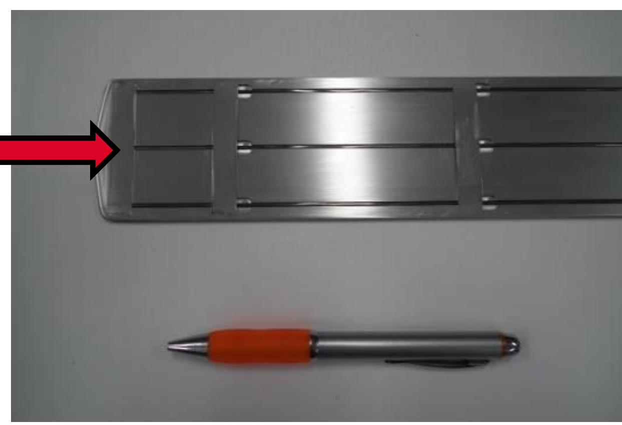
# 3. Examples of in-core instrumentation
# 3.1. Neutron and gamma flux

## Application of fission chambers :
## Neutron profile measurements between fuel plates in OPAL reactor (2013)

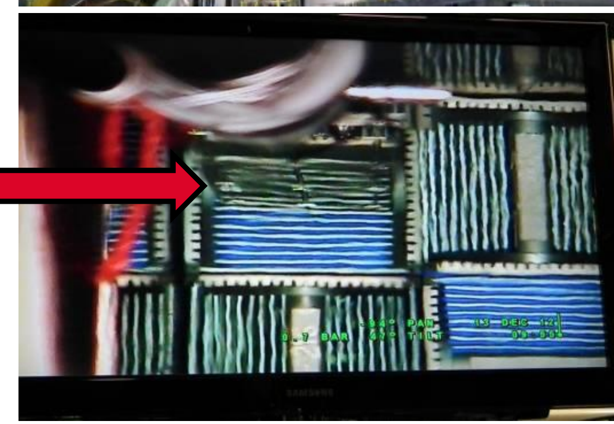
- 3 x Ø1.5mm Fission Chambers
- Dedicated Experimental Rig:
  2mm thick aluminium plate attached to a 16 meter long pole
  - Correct and repeatable positioning
  - Precise manoeuvring within the core
- OPAL Reactor operated at stabilized power 100 kW



**Ø1,5 mm Fission Chambers for three simultaneous neutron profiles**



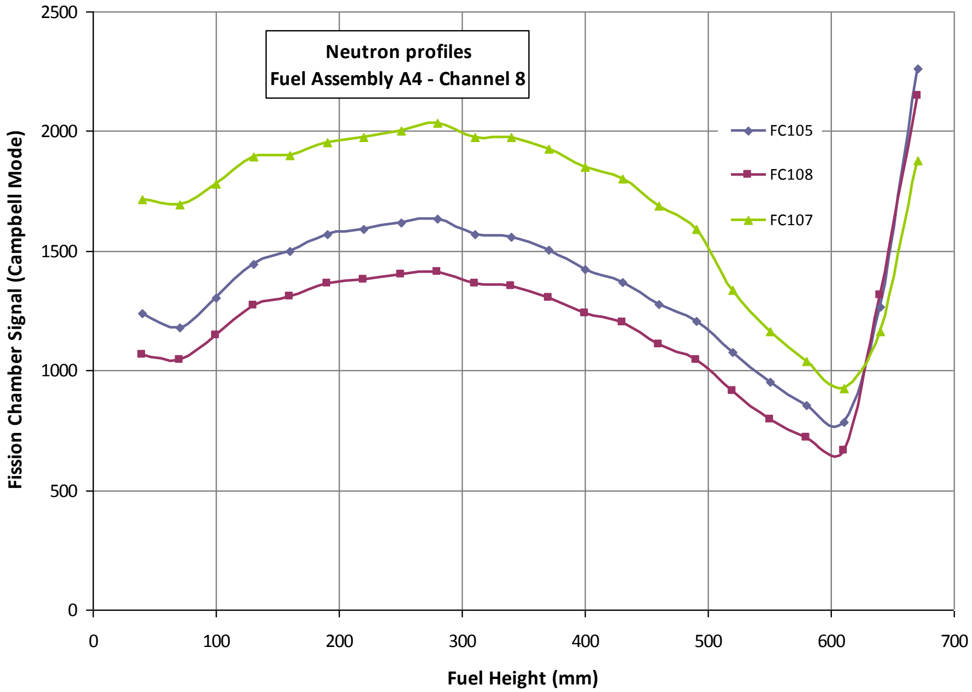
**Experimental rig**



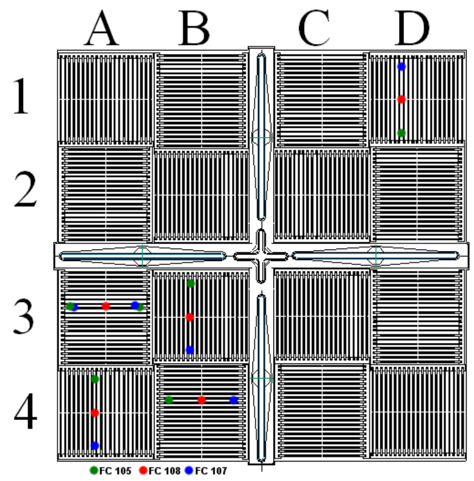
**Insertion between fuel plates**

### Application of fission chambers : Neutron profile measurements between fuel plates in OPAL reactor (2013)

- 400 measurement points
- Thorough investigation of 5 / 16 fuel assemblies:
  - One complete quadrant
  - One fresh fuel assembly in another quadrant
- Good agreement with expected neutron flux shapes




Measurement Locations



# 3. Examples of in-core instrumentation

## 3.2. Temperature

# Temperature measurements

## Objectives :

**Online measurement of materials or fuels temperature**

Typical range : 200-400°C (PWR materials) up to 1200°C (fuel)

1000-1600°C for transient / study of incidental conditions

## State-of-the-art :

- **MIMS thermocouples : type K, N, C**
- Expansion thermometers (LVDT)
- Melt wires, paint spots and SiC monitors (post-irradiation analysis)

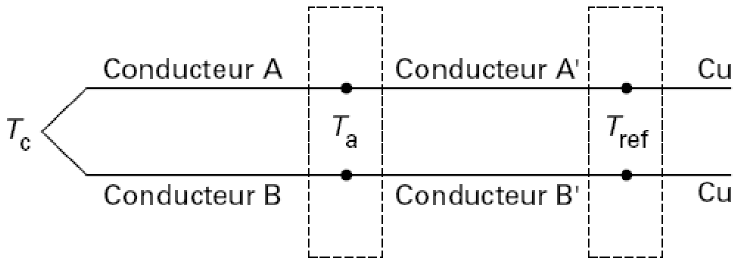
## Developments :

- High-temperature doped Mo/Nb alloy thermocouples
- In-situ calibration of thermocouples :
  - Noise thermometry
  - High-temperature fixed-point μ-cell
- Ultrasonic sensors
- Infrared pyrometer
- **Distributed temperature measurements with Optical Fibers**

# Thermocouples

**Principle : Seebeck effect**

An electromotive force is generated in an open circuit made of 2 different conducting materials, when their junctions are at different temperatures




## Characteristics of in-core thermocouples :

**Couples :**

type K or type N (up to 1100 °C depending on wire diameter)
type C (fuel centerline temperature, for short irradiation time)

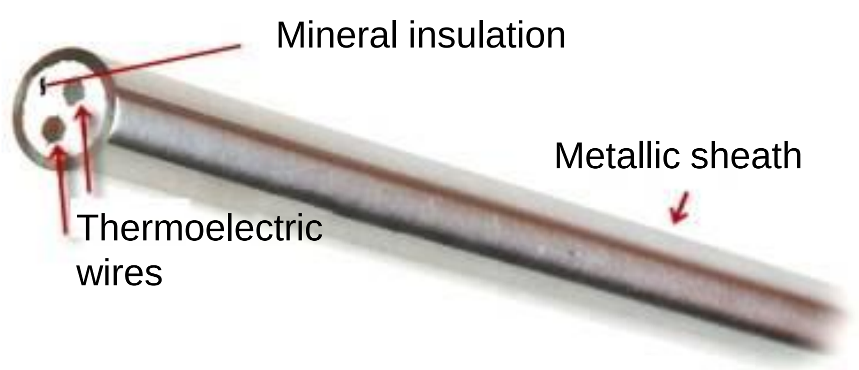
**Sheath :** Stainless steel (304L, 316L, 347)

**Insulator :** $Al_2O_3$, MgO, $HfO_2$

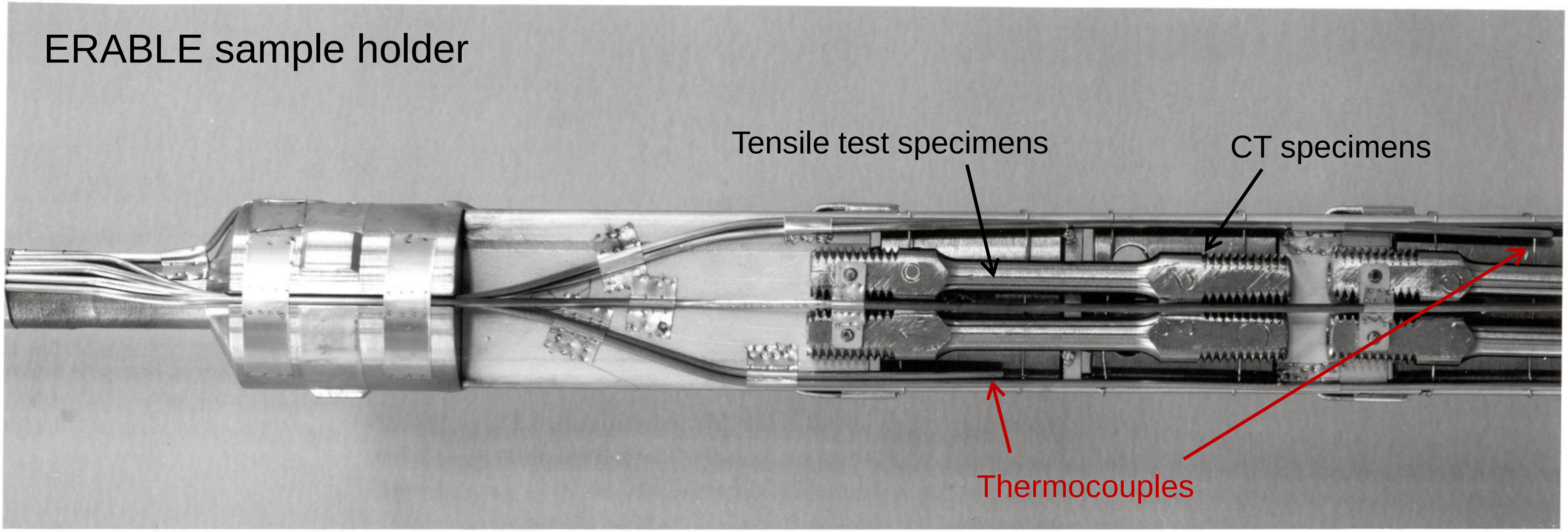
**Standard sheath diam. :** 1 mm
**Standard wire diam. :** ~ 0,2 mm

**Hot junction insulated from sheath**

**Length :** tens of meters

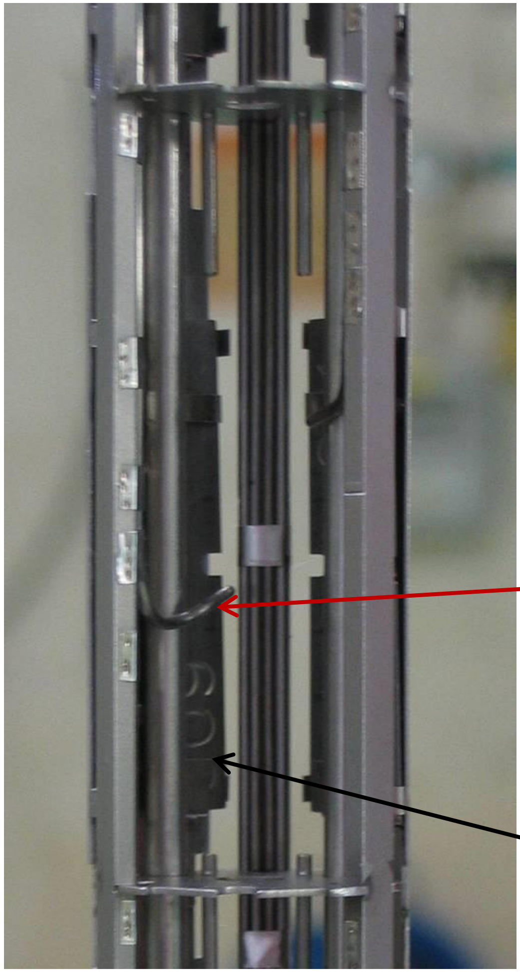


# Thermocouples
# Examples of implantation in MTR experiments

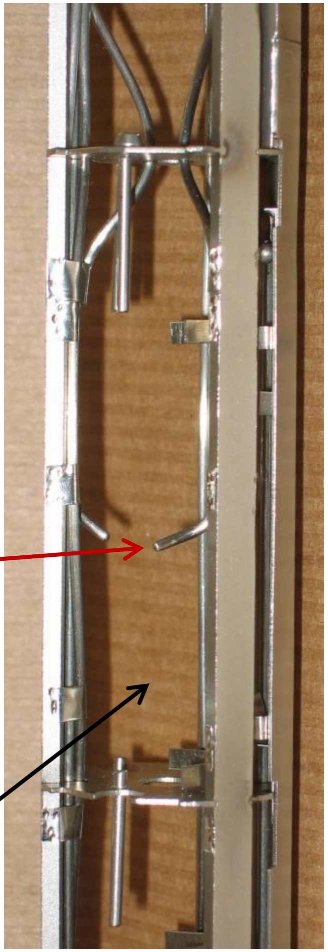


# 3. Examples of in-core instrumentation
## 3.2. Temperature

## Thermocouples
## Examples of implantation in MTR experiments



CARDINAL sample holder

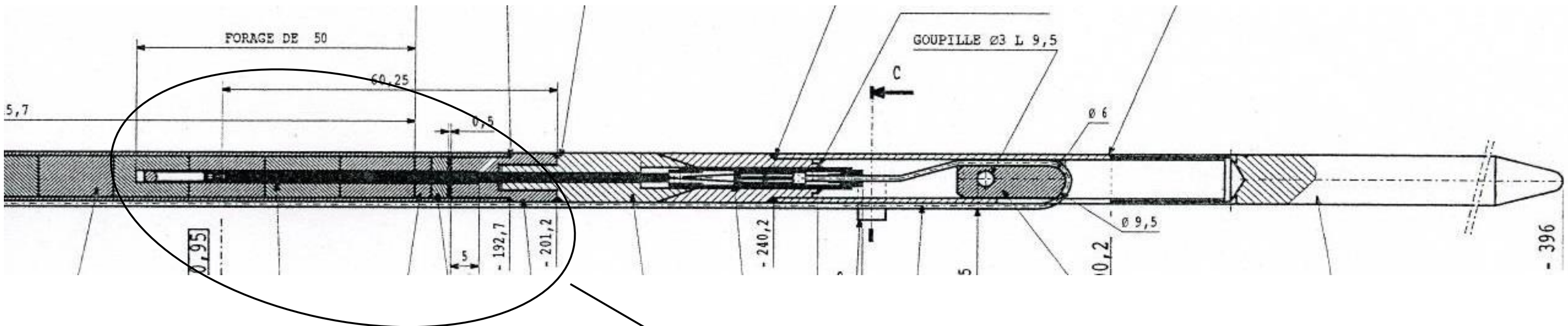


Thermocouples

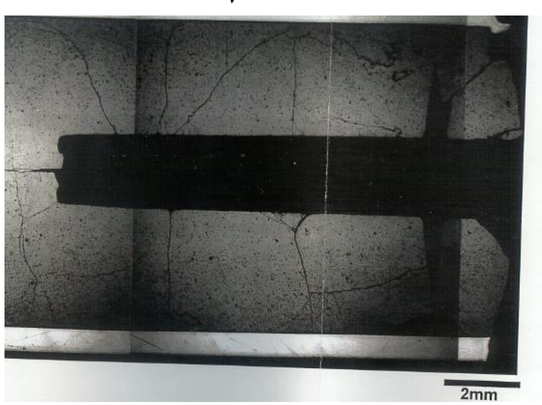
Location of specimens
for creep or growth study

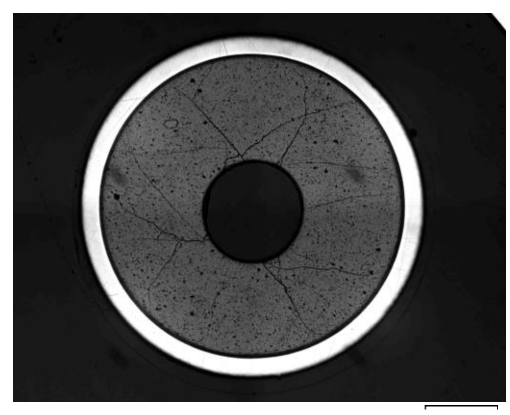
# 3. Examples of in-core instrumentation
## 3.2. Temperature

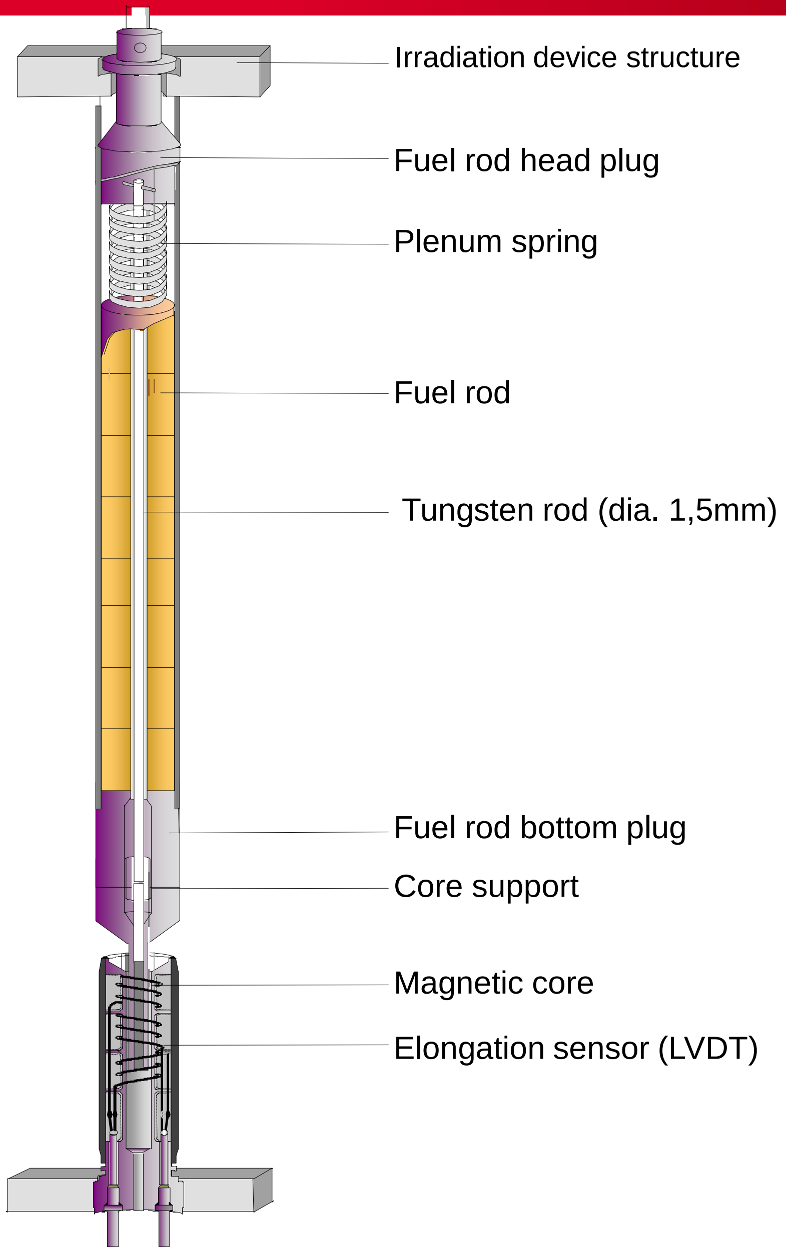
## Thermocouples
## Examples of implantation in MTR experiments for fuel centreline temperature measurements




Drilled pellets






## Expansion thermometer

**Measures the expansion of a metallic rod**

+ robust

+ suitable for very high temperatures

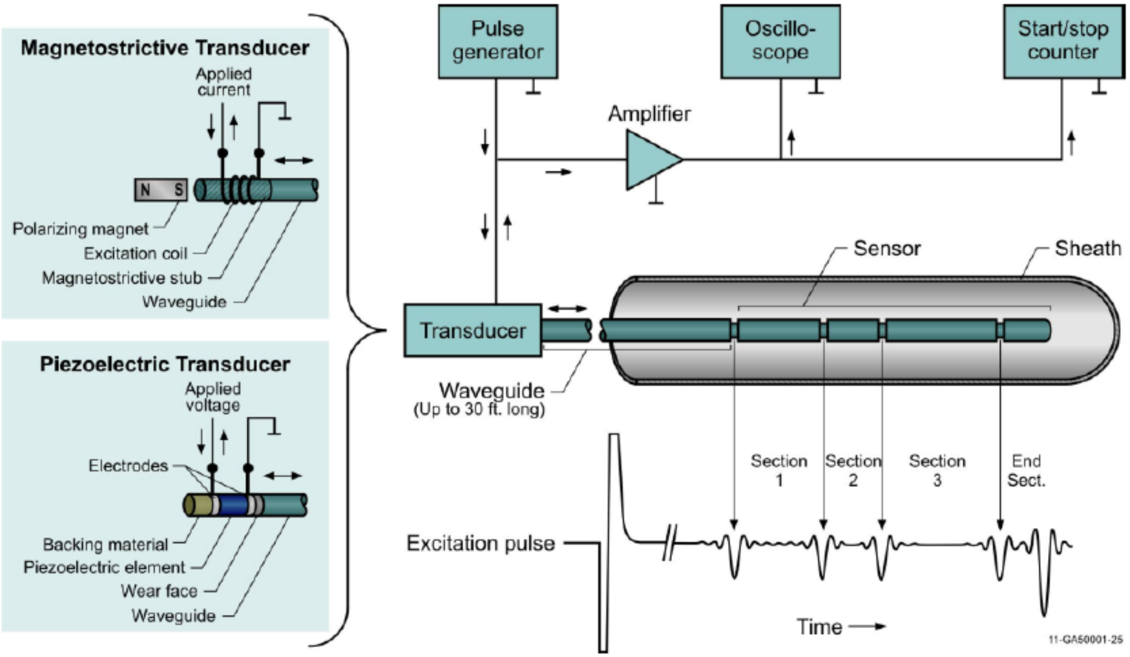
- integrated temperature

- very intrusive

## Ultrasonic sensors

Measures the acoustic wave velocity in a metallic rod or wire

Notches → wave reflection (echoes)
→ Detection of acoustic wave velocity changes between notches




→ High-temperature measurements (> 2000°C)

→ Distributed measurements

## Melt wires

Based on the detection of wire melting

| Material Composition, % | Melting Temperature, °C |
|---|---|
| 100 Pb | 327.5 |
| 94 Zn-6 Al | 381.0 |
| 85 Te-15 Sn | 401.0 |
| 100 Zn | 419.6 |
| 80 Sb-20 Zn | 507.8-514.3 |

→ Easy implementation (no cable)

But - post-irradiation measurement

- only indicates that melting temperature has been reached

Idaho National Laboratory

# 3. Examples of in-core instrumentation

## 3.3. Innovative technologies : micro-acoustics & fiber optics

## Acoustic measurement of fission gas release

Objective : **Online measurement of fission gas release in a pressurized fuel rod** with discrimination between fission gas release –mainly Xe and Kr and He discharge
This distinction is not possible using only pressure and temperature measurements.

Principle : development of dedicated acoustic instrumentation

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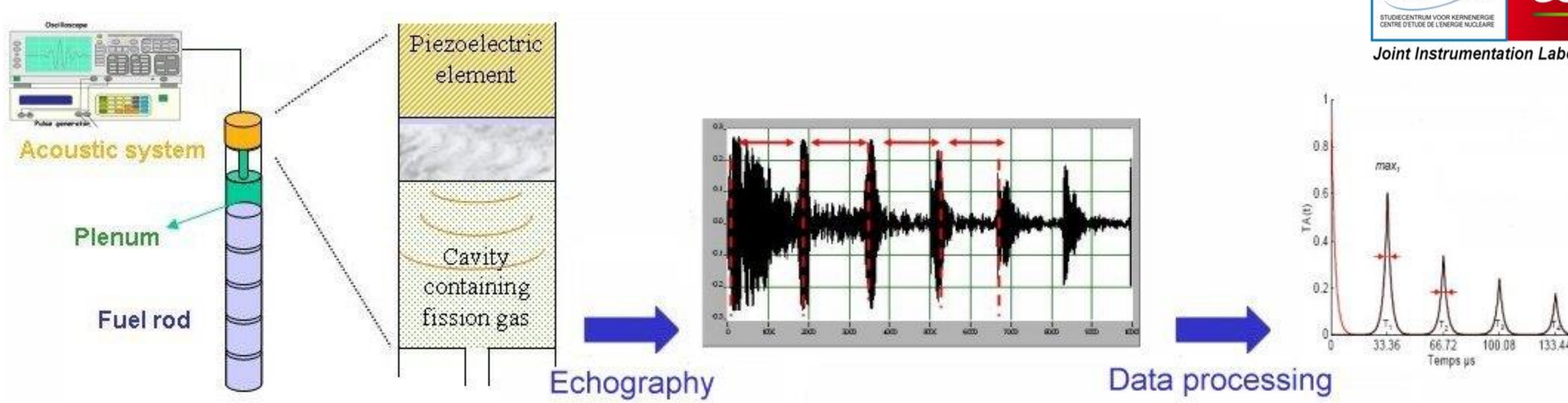
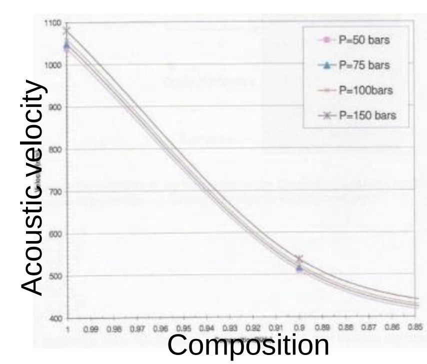



- Acoustic waves velocity → gas composition (= molar mass)
- Echoes attenuation → gas pressure

$$v = \sqrt{\frac{\gamma RT}{M}}$$

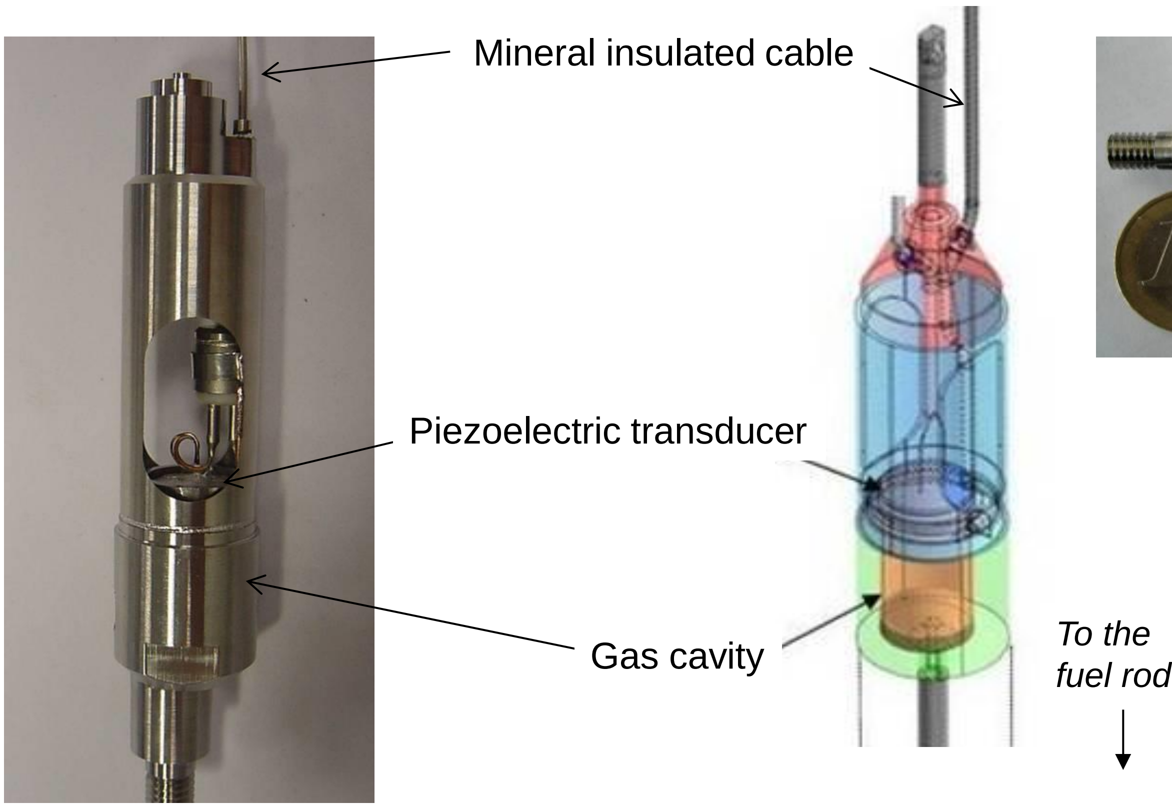


# 3. Examples of in-core instrumentation
## 3.3. Innovative technologies : micro-acoustics

## Acoustic measurement of fission gas release

→ **An original sensor was designed for MTR irradiation**

Patented



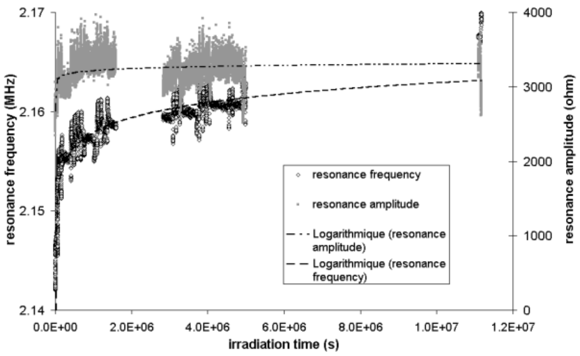

**The sensor is designed to be implemented on a pre-irradiated fuel-rod**

SCK•CEN / cea
*Joint Instrumentation Laboratory*

# Acoustic measurement of fission gas release

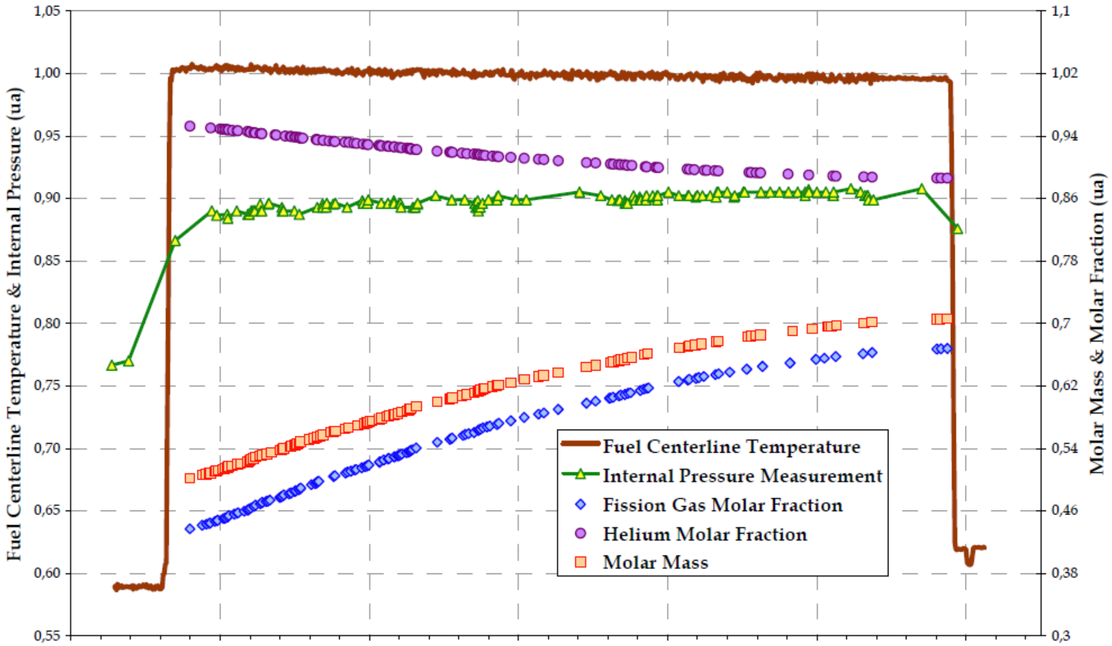
→ **Successive tests performed :**

- Tests of piezoelectric transducers in BR1 reactor
- Sensor qualification test in OSIRIS reactor




→ **Successful implementation in REMORA-3 experiment in OSIRIS :**

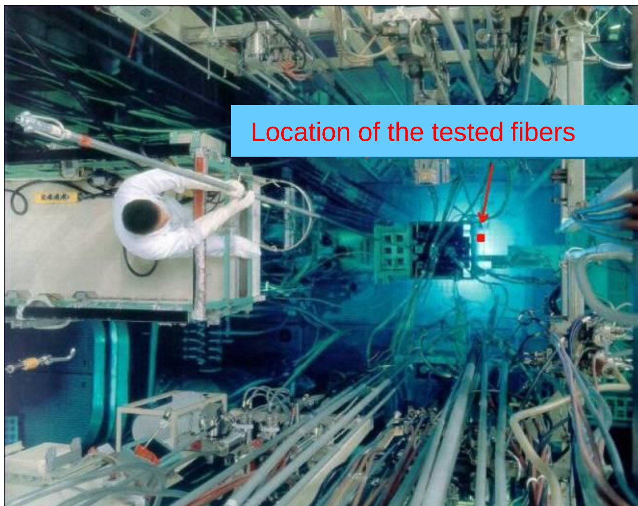
- Sensor installed on a 5 cycle pre-irradiated PWR MOX fuel rod
- World first experiment with online measurement of fission gas release in a pressurized fuel rod



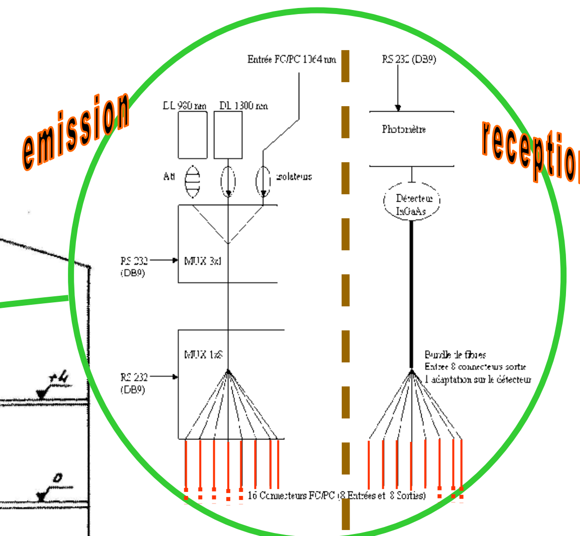
# 3. Examples of in-core instrumentation
## 3.3. Innovative technologies : fiber optics

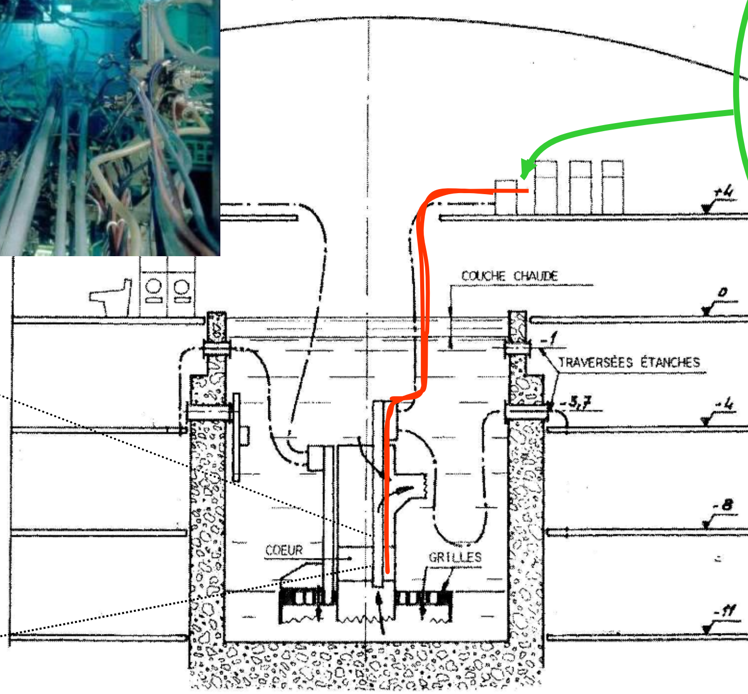
## Recent results : new fibers can survive in-core

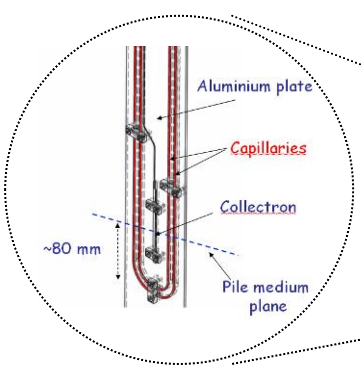
Example : COSI experiment (OSIRIS reactor, France – 2006)




Irradiation of 12 recently developed optical fibers



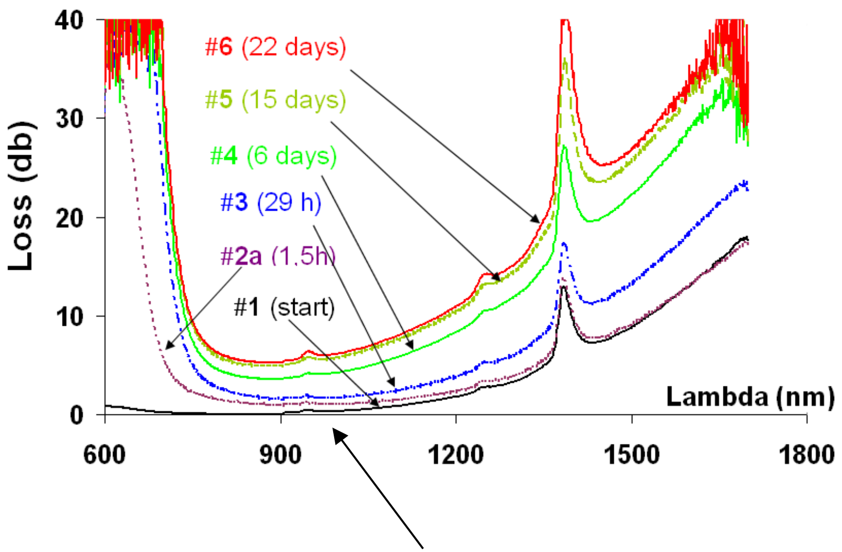

92 days of reactor operation

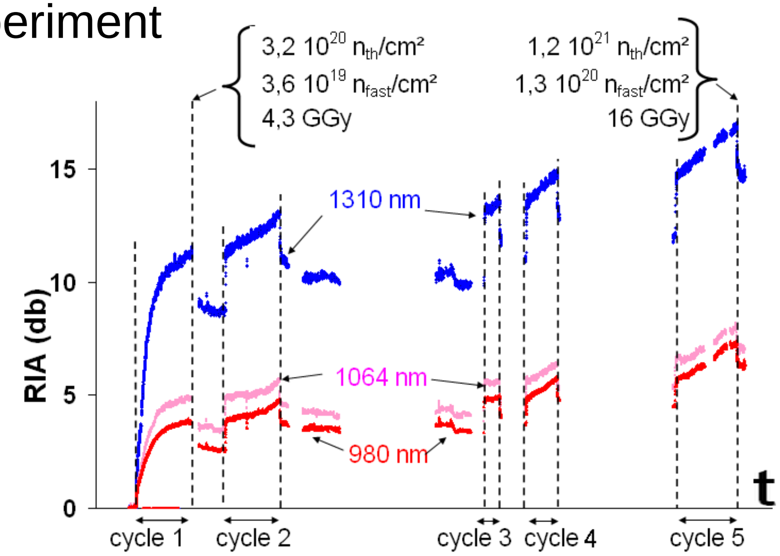
→ Dose > 1E20 $n_{fast}/cm^{-2}$

> 16 GGy

## Recent results : new fibers can survive in-core

Some results from COSI experiment



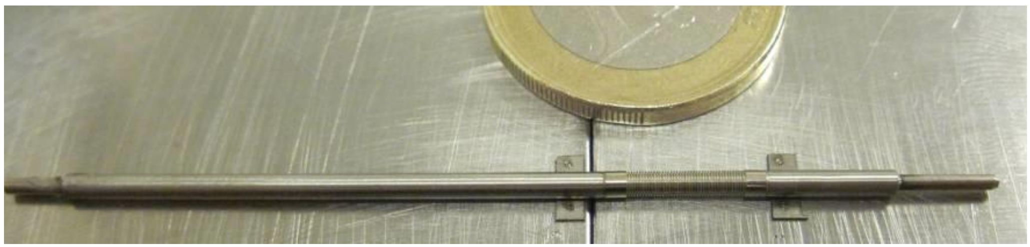




- Favorable spectral region in the 800-1200 nm range
- RIA measured losses < 10 dB → suitable multimode and single mode fibers exist for in-core applications

Better choose measurement systems that do not rely on light intensity
→ *interferometry (Fabry-Perot, Bragg gratings…)*

# Example of fiber-based in-core sensor : optical extensometer

## Nuclear-grade elongation Fabry-Perrot type sensors



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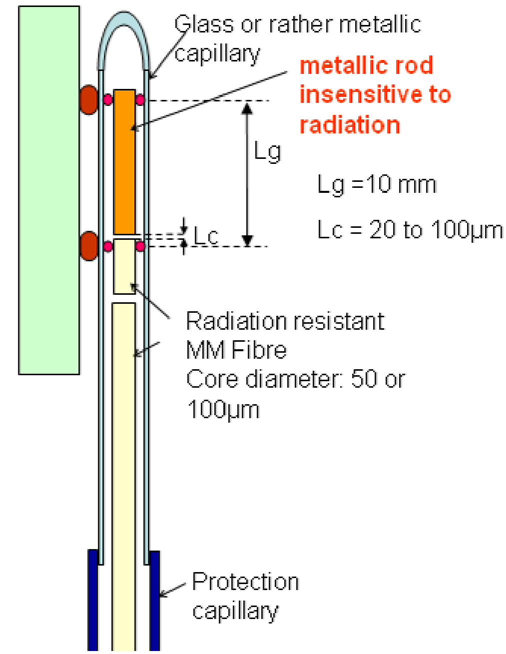
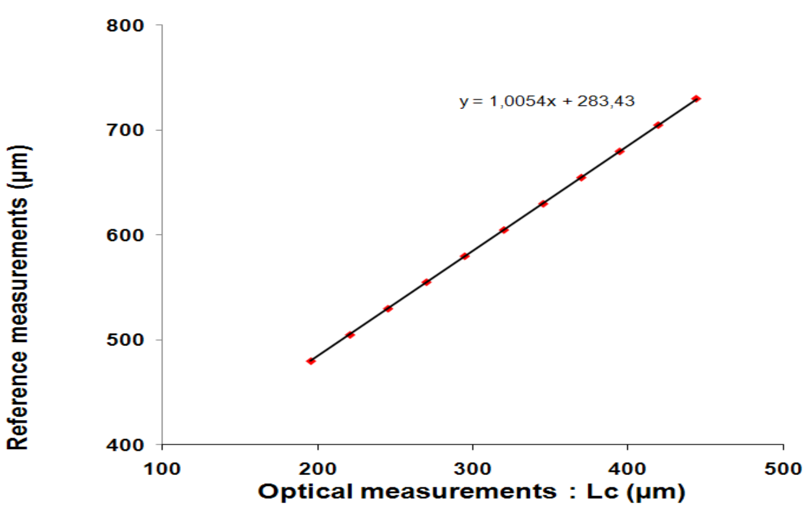
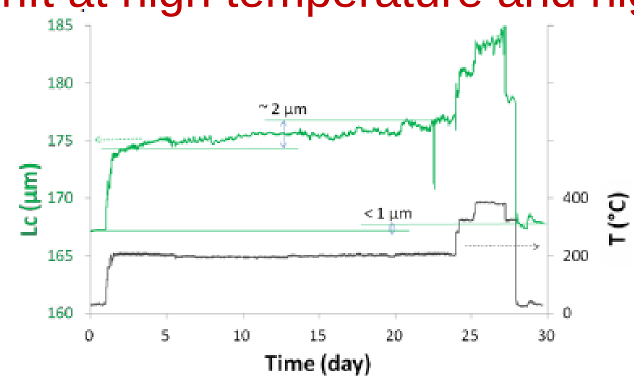



- Adaptation to high T (400°C), with HT resistant fiber (*Cuball*, Al, Au coating)
- Better sensor-sample sealing
- Increased accuracy (1µm/100µm) and temperature compensation



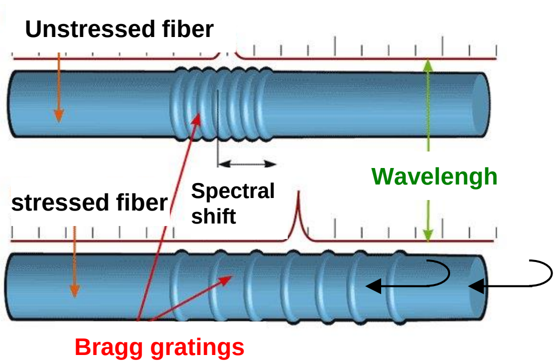

→ Low drift at high temperature and high flux

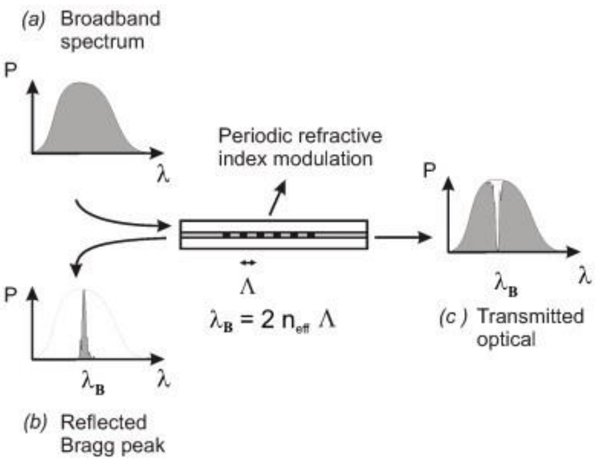


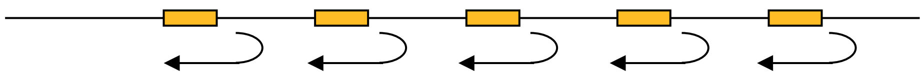
# In-core optical measurements

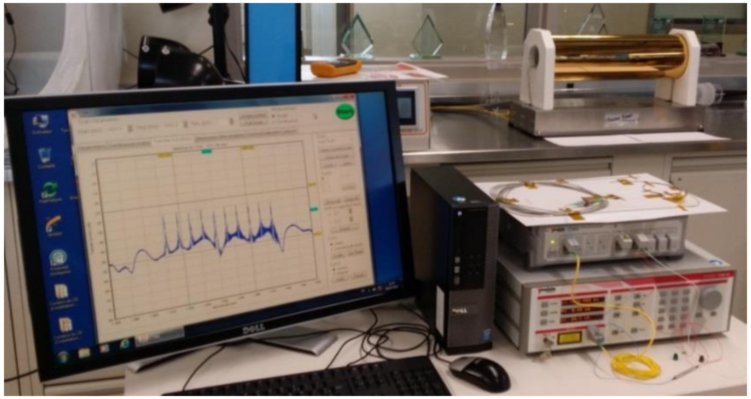
- Fabry-Perot sensor is now in a phase of industrial transfer
- Other developments : **Bragg Grating sensors**

**= distributed measurements of temperature / deformation**





→ *On-going tests at the MITR*
→ *Scheduled tests at the ATR and BR2*

# 4. Review of MTR instrumentation around the World

# 4. Review of MTR instrumentation around the World

Instrumentation Technologies at SCK·CEN, CEA, JAEA, KAERI, IFE/HRP, INL and NRG

| Research Organization/Country | Technology | | |
|---|---|---|---|
| | Sensors | Parameter Detection | Status |
| Studiecentrum voor Kernenergie • Centre d'Étude de l'Énergie Nucléaire (SCK•CEN)/Belgium | SPNDs | Thermal flux | Operational |
| | Fission chambers | Thermal and fast flux | Operational (fast detectors qualified in 2009 in the framework of Joint Lab with CEA) |
| | Fiber optics | Length | Under development (Joint Lab with CEA) |
| | Linear variable differential transformers (LVDTs) with unstressed bellows and stressed bellows. | Length/creep-induced elongation | Participating in qualification testing with VTT (LVDTS provided by IFE/HRP) |
| | Flux wires, foils, and melt wires | Fluence (neutron) and temperature | Operational |
| Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)/France | Fission chambers (down to 1.5 mm diameter) | Thermal and fast flux | Operational (fast detectors qualified in 2009 in the framework of Joint Lab with SCK•CEN) |
| | SPNDs | Thermal flux | Operational |
| | SPGDs | Gamma flux | Operational |
| | Activating foils | Integral flux | Operational |
| | Gamma calorimeter | Nuclear heating | Operational |
| | Thermocouples and melt wires | Temperature | Type K, N, and C thermocouples—Operational; can be placed in previously irradiated fuel rods. Mo/Nb alloys thermocouples under development with French vendor (Thermocoax) (long-duration testing) |
| | Noise thermometry | Temperature | Under development |
| | Counter-pressure sensor | Fission gas release (pressure in fuel rod) | Operational (placed on previously irradiated fuel rod) |
| | Acoustics | Fission gas composition and pressure | Operational (placed on previously irradiated fuel rod) |
| | LVDTs | Length/creep-induced elongation<br>Diameter gauge | Operational (also testing enhanced IFE/HRP LVDTs) under development (testing enhanced IFE/HRP DGs) |
| | Fiber optics | Length | Under development (Joint Lab with SCK•CEN) |

(Continued)

# 4. Review of MTR instrumentation around the World

| Research Organization/Country | Technology | | |
|---|---|---|---|
| | Sensors | Parameter Detection | Status |
| Japan Atomic Energy Agency (JAEA)/Japan | Fission chambers (1.8 mm diameter) | Thermal flux (with $^{235}U$ deposits) | Operational |
| | SPNDs | Thermal flux (Rh, Co, and Pt-40%Rh emitters) | Operational |
| | Flux wires | Integral fast (Fe) and thermal (Al-Co, V-Co, and Ti-Co) flux | Operational |
| | Thermocouples (Type K, N, and C) and melt wires | Temperature | Operational (subject to high temperature or transmutation-induced signal degradation; can place in previously irradiated fuel rods. |
| | LVDT (stressed with bellows and unstressed) | Pressure, length/creep-induced elongation | Operational (using Japanese-made LVDTs and bellows) |
| | DCPD method with CT specimens and bellows loading | Crack growth | Operational |
| Korea Atomic Energy Research Institute (KAERI)/Korea | Thermocouples (Type K and C) and melt wires | Temperature | Operational |
| | Flux wires | Integral fast flux | Operational |
| | LVDTs | Pressure, $UO_2$ elongation/creep-induced elongation | Operational for pressure and fuel elongation detection/under evaluation for creep testing (using IFE/HRP LVDTs) |
| | SPNDs (V-, Rh-emitter) | Thermal flux | Operational (using commercially-made SPNDs) |
| Institute for Energy Technology/Halden Reactor Project (IFE/HRP)/Norway | LVDT (stressed with bellows and unstressed) | Pressure, length/creep-induced elongation, diameter | Operational (enhancements explored with CEA and INL) |
| | Eddy-current probe | Oxide thickness deposited on fuel rods | Under development |
| | Thermocouples (Type K, N, and C) and melt wires | Temperature and thermal conductivity degradation | Operational (subject to high temperature or transmutation-induced signal degradation). Can place in previously irradiated fuel rods. |
| | SPNDs | Thermal flux, power, fuel heat-up rate | Operational (using commercially-made and IFE/HRP-made sensors) |
| | Gamma thermometer | Heat generated by gamma heating | Operational (using IFE/HRP-made sensors) |
| | DCPD method with CT specimens and bellows loading | Crack growth | Operational |

(Continued)

# 4. Review of MTR instrumentation around the World

| Research Organization/Country | Technology | | |
|---|---|---|---|
| | Sensors | Parameter Detection | Status |
| Institute for Energy Technology/Halden Reactor Project (IFE/HRP)/Norway (continued) | Electrochemical corrosion potential probes | Water chemistry | Operational |
| | Flux wires | Integral fast (Fe, Ni) and thermal (Al-Co) flux | Operational |
| | Melt wires (peak) | Temperature | Operational |
| Idaho National Laboratory (INL)/U.S. | Melt wires (peak), SiC temperature monitors (range) | Temperature | Operational |
| | Thermocouples (Type N, K, C, and doped Mo/Nb-alloy HTIR-TC) | Temperature | Operational (HTIR-TCs developed and offered by INL) |
| | Hot wire probe | Thermal conductivity | Final laboratory evaluations underway; scheduled for irradiation testing in 2011. |
| | Ultrasonic transducers | Length/geometry | Under laboratory evaluation |
| | Ultrasonic thermometers | Temperature | Under laboratory evaluation |
| | Flux wires and foils | Fluence (neutron) | Operational |
| | Gas chromatography<br>Pressure sensors<br>Gamma detectors/sampling | Fission gas (amount, composition) | Operational |
| | LVDT (stressed with bellows and unstressed) | Length/creep-induced elongation | Under laboratory evaluation (using IFE/HRP LVDTs); irradiation scheduled for 2011. |
| | SPNDs (Rh, Gd, and Hf emitters) | Thermal flux | Under evaluation at ATR Critical (ATRC) facility |
| | Miniature and subminiature fission chambers | Fast and thermal flux | Under evaluation at ATR Critical (ATRC) facility |
| Nuclear Research & Consultancy Group (NRG)/ Netherlands* | Flux wires (Nb, Ti, Fe, NiCo) | Fluence (neutron) | Operational |
| | SPNDs | Thermal flux, power, fuel heat-up rate | Operational (using commercially-made SPNDs) |
| | Thermocouples (Type K and N) | Temperature | Operational |
| | LVDT | Pressure | Operational (using IFE/HRP LVDTs) |
| | Silicon chip transducer | Pressure | Operational (using kulite semiconductor products outside high neutron and gamma radiation locations) |

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