IRRADIATION TESTS IN RESEARCH REACTORS

INSPYRE summerschool

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CONTENT

1. MATERIAL TEST REACTORS

CONDITIONS IN MATERIAL TEST REACTORS

MTRs are quite different from Nuclear Power Plants (NPP’s) in the fact that the produced neutrons are used for experiments and isotope-production in stead of electricity.

→ low coolant water temperature

  → low pressure environment

  → possible use of aluminium as construction material

High neutron flux is required to speed up the aging of materials and (maybe) the burn-up of fuels

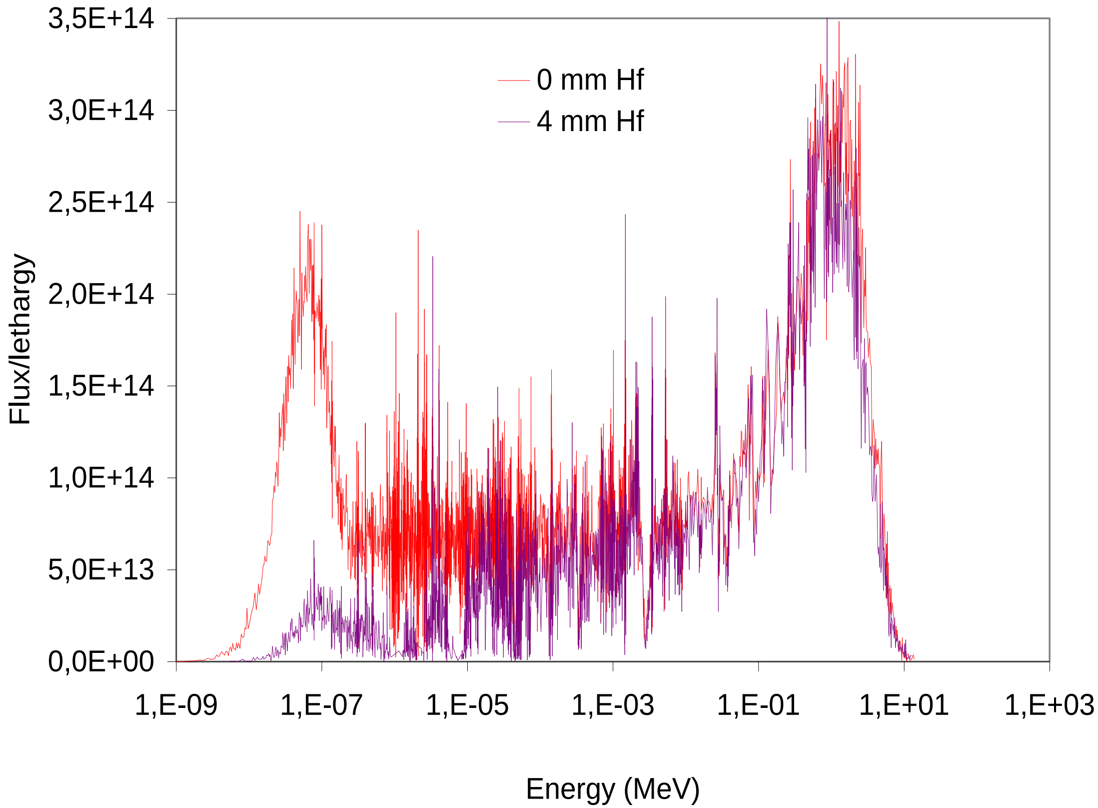
→ higher fissile isotope density required (U atomic density, enrichment)

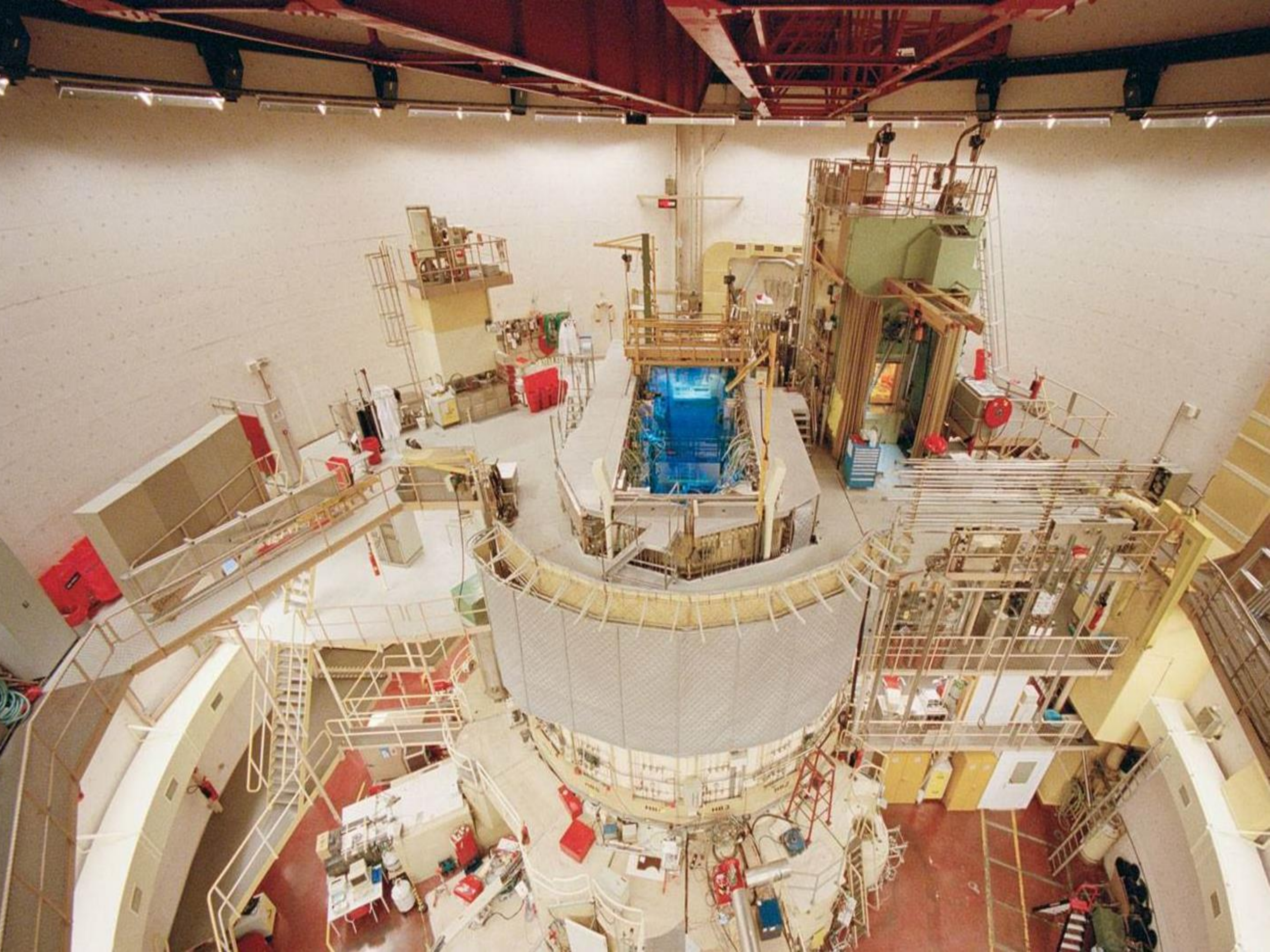
  → Use of U_3Si_2 plates at ~20% enrichment in U-235

The reactor needs open spaces to insert ‘rigs’ (experiments or isotope production rigs)

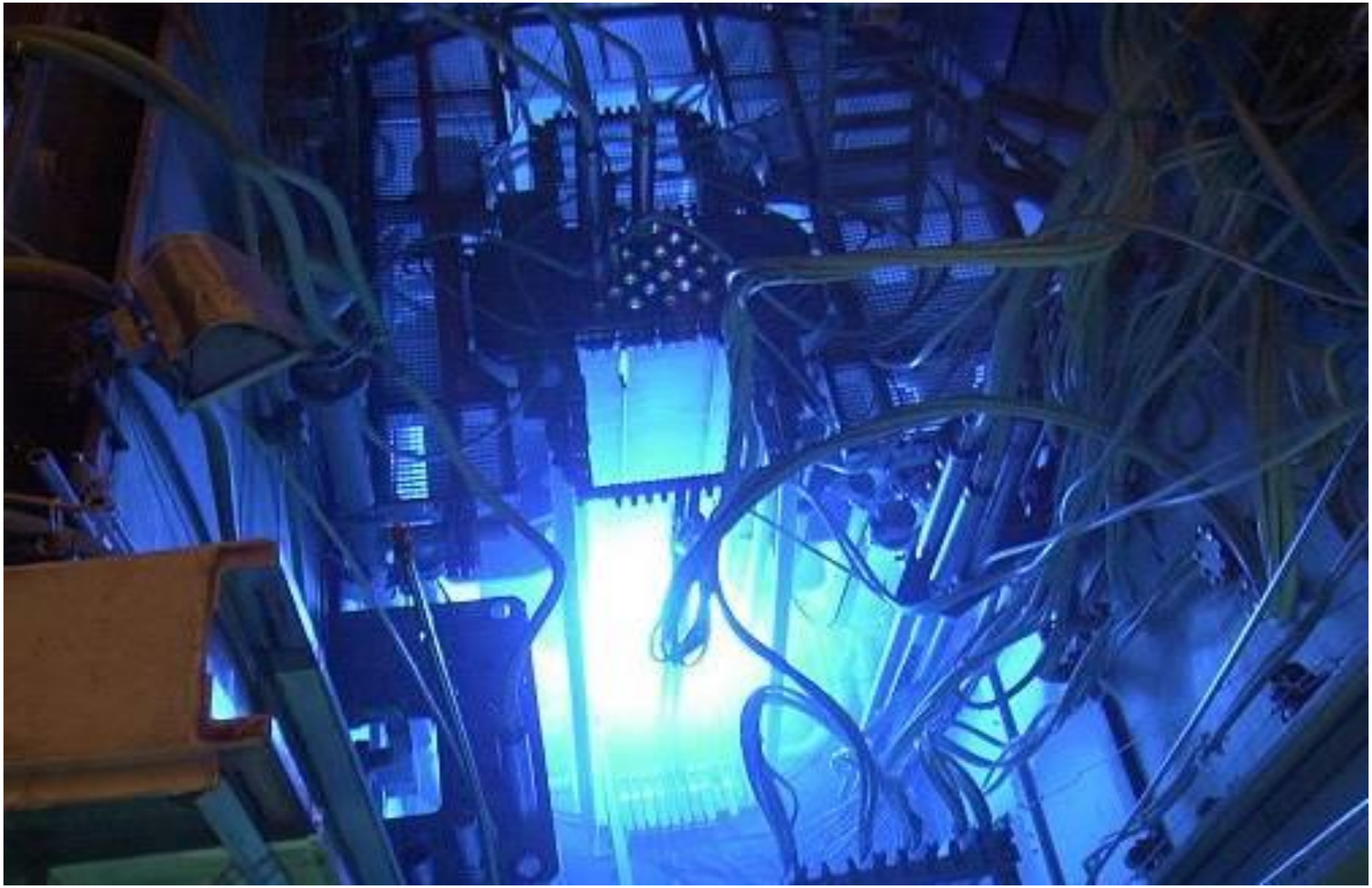
NEUTRON FLUX AND SPECTRUM

- Most MTRs are water-cooled, and their spectrum is usually somewhat softer than that of LWRs
- Simplified description of spectrum in terms of:
  - Fast region: DPA's
  - Thermal region: transmutation (fission) rates
- Experimenters have the option of 'spectral matching':
  - Shielding (Cd, Hf)
  - Additional moderation (water, graphite)

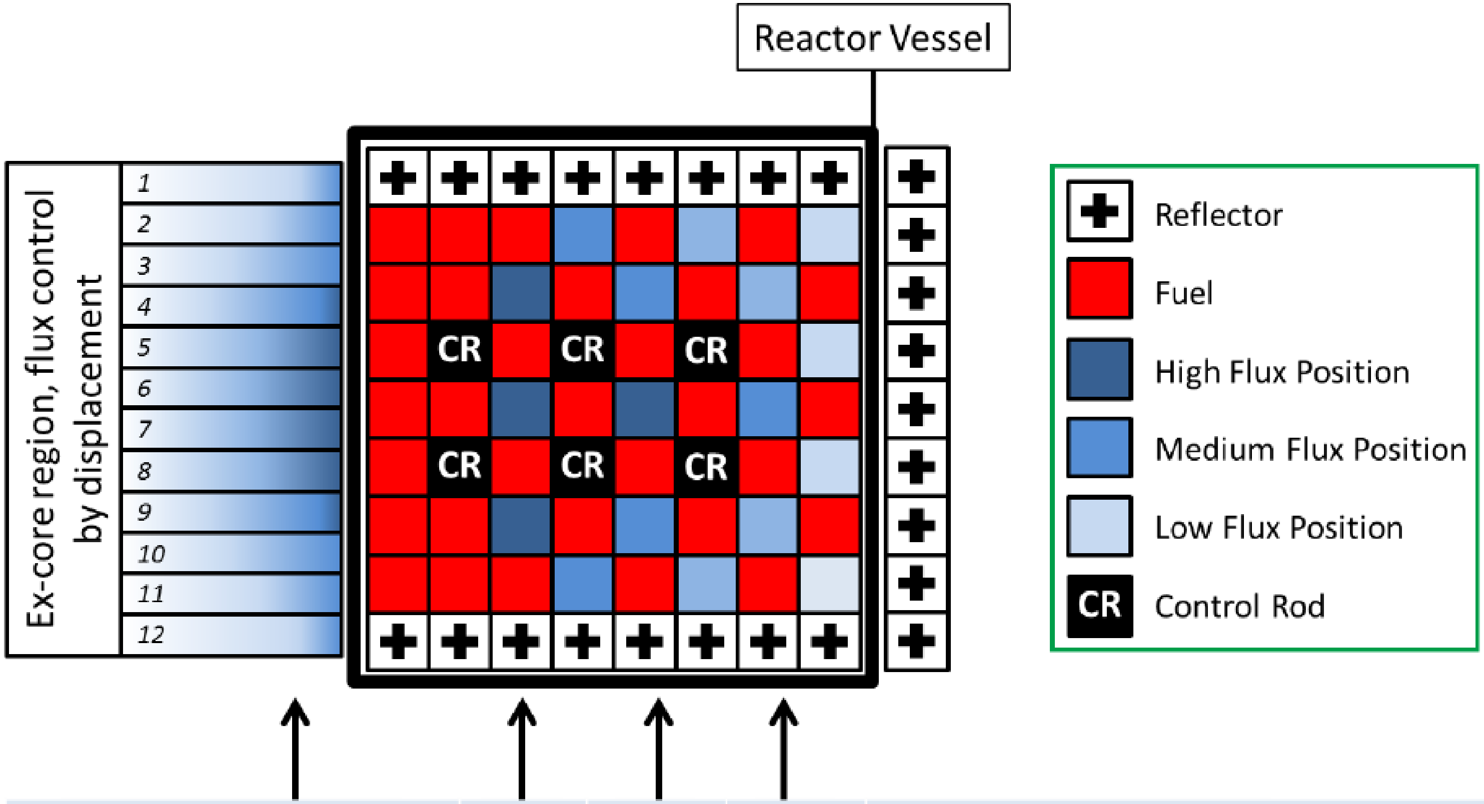



HB3

HFR CORE



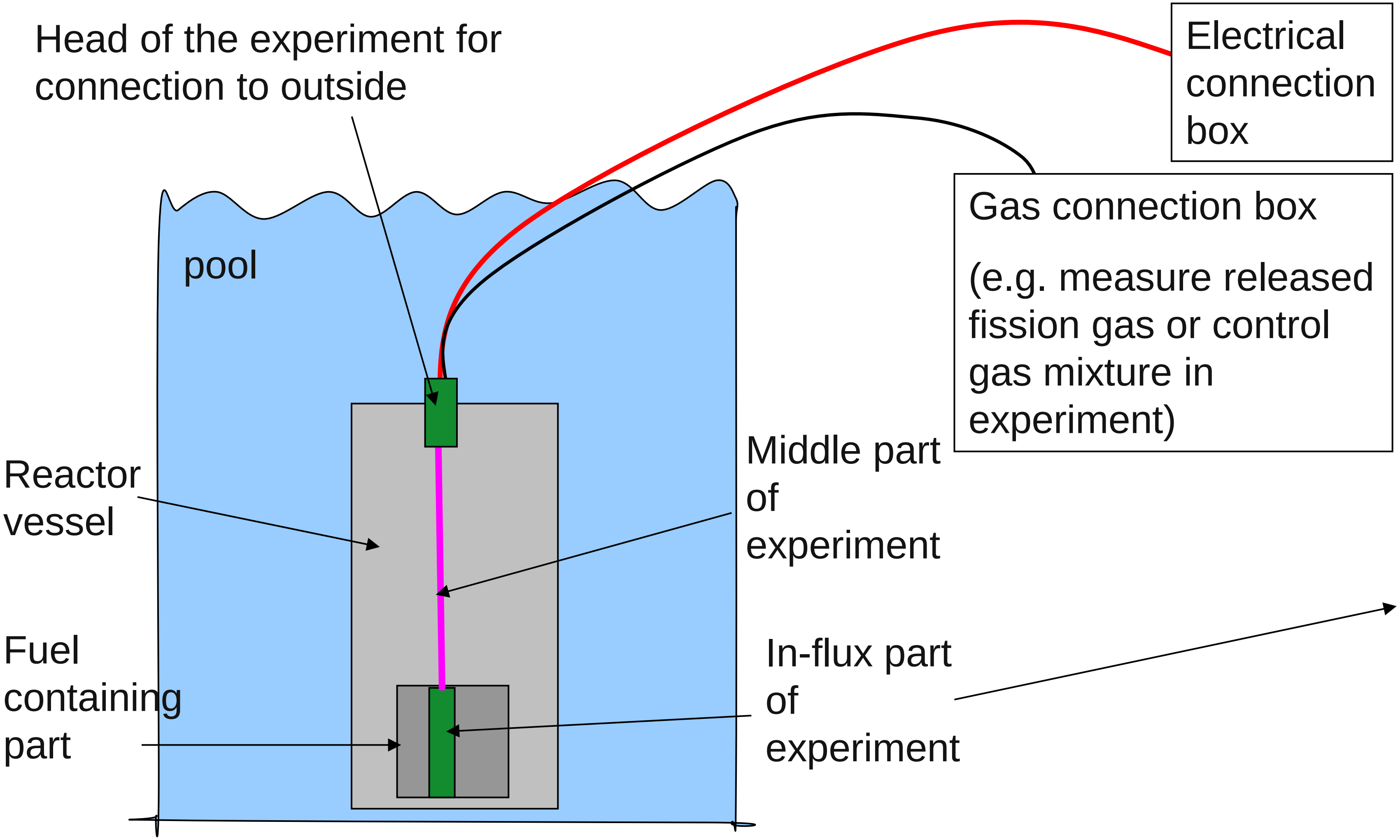
HFR CORE LAY-OUT



0-3, location dependent	5-8	3-5	1-3	Material DPA rate (DPA/year)
0-700, displacement controlled	n/a	500-700	300-400	Linear heat rate (W/cm fresh LWR fuel)

The stable and constant flux profile in each irradiation position is a unique HFR feature

CAPSULE EXPERIMENT LAY-OUT



Head of the experiment for connection to outside

Electrical connection box

Gas connection box

(e.g. measure released fission gas or control gas mixture in experiment)

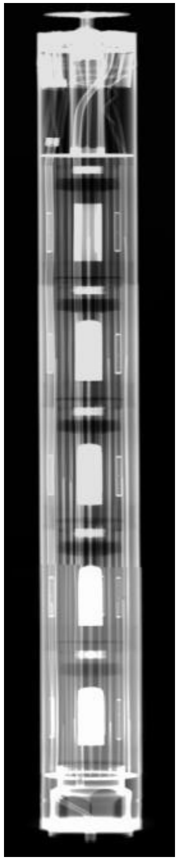
pool

Reactor vessel

Middle part of experiment

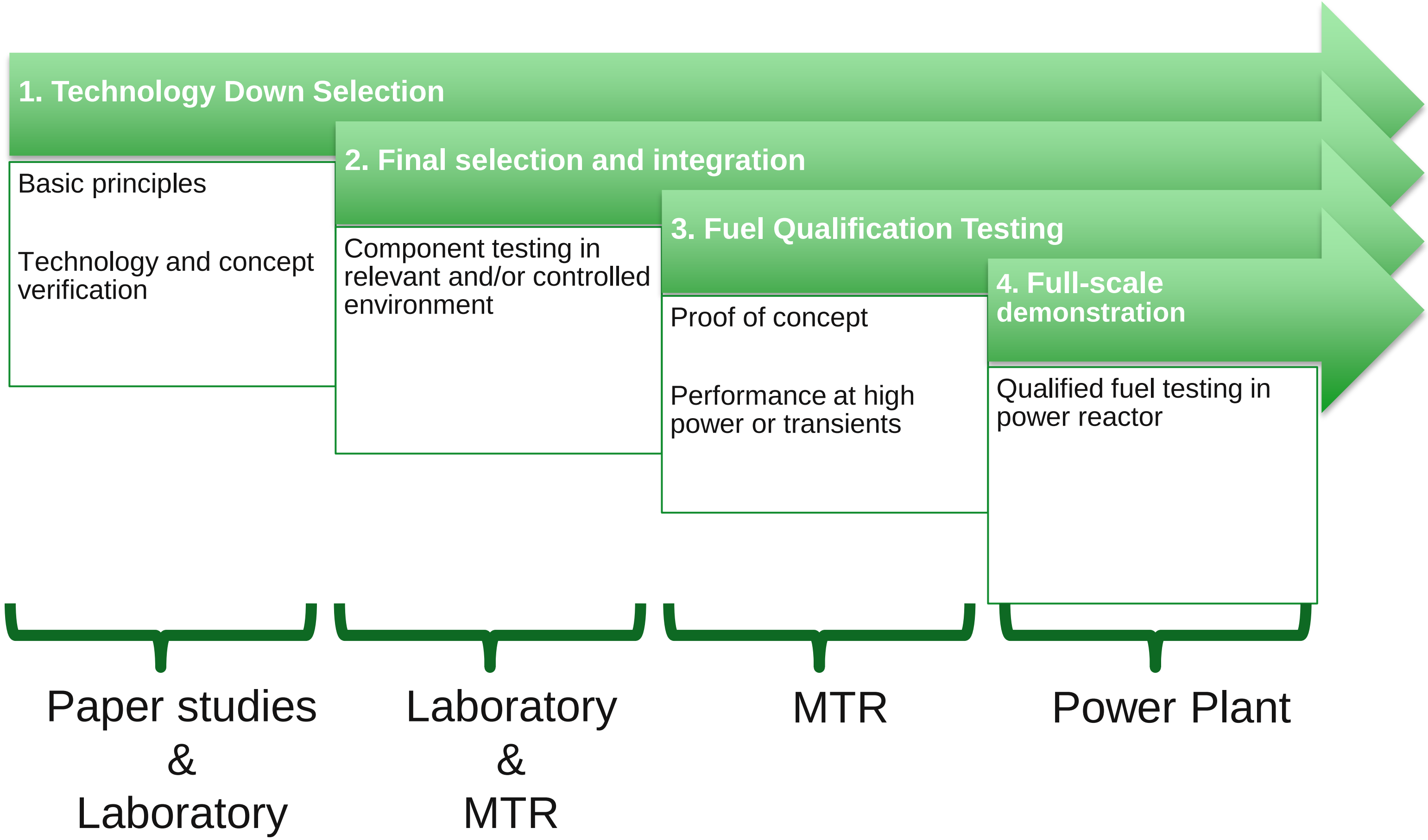
Fuel containing part

In-flux part of experiment



2. FUEL EXPERIMENT TYPES

FUEL DEVELOPMENT



1. Technology Down Selection

Basic principles

Technology and concept verification

2. Final selection and integration

Component testing in relevant and/or controlled environment

3. Fuel Qualification Testing

Proof of concept

Performance at high power or transients

4. Full-scale demonstration

Qualified fuel testing in power reactor

Paper studies
&
Laboratory

Laboratory
&
MTR

MTR

Power Plant

‘INTEGRAL’ VS ‘SEPARATE EFFECTS’

Integral tests are simulations of <u>‘the real thing’</u>.

- Carried out to:
  - Provide proof of safe behavior within a set of conditions
  - Confirm predictions of fuel performance codes
  - Determine failure criteria for fuel performance codes
- Nominal conditions, maximum/extreme conditions, transients

Separate effects tests provide data on material behavior at a set of <u>well-defined conditions</u> (temperature, pressure etc.)

- Ideally, varying one parameter *ceteris paribus*
- Carried out to provide input data for:
  - mechanistic models
  - fuel performance codes

‘INTEGRAL’ VS ‘SEPARATE EFFECTS’

Separate effects test

input parameters

Fuel Performance Code

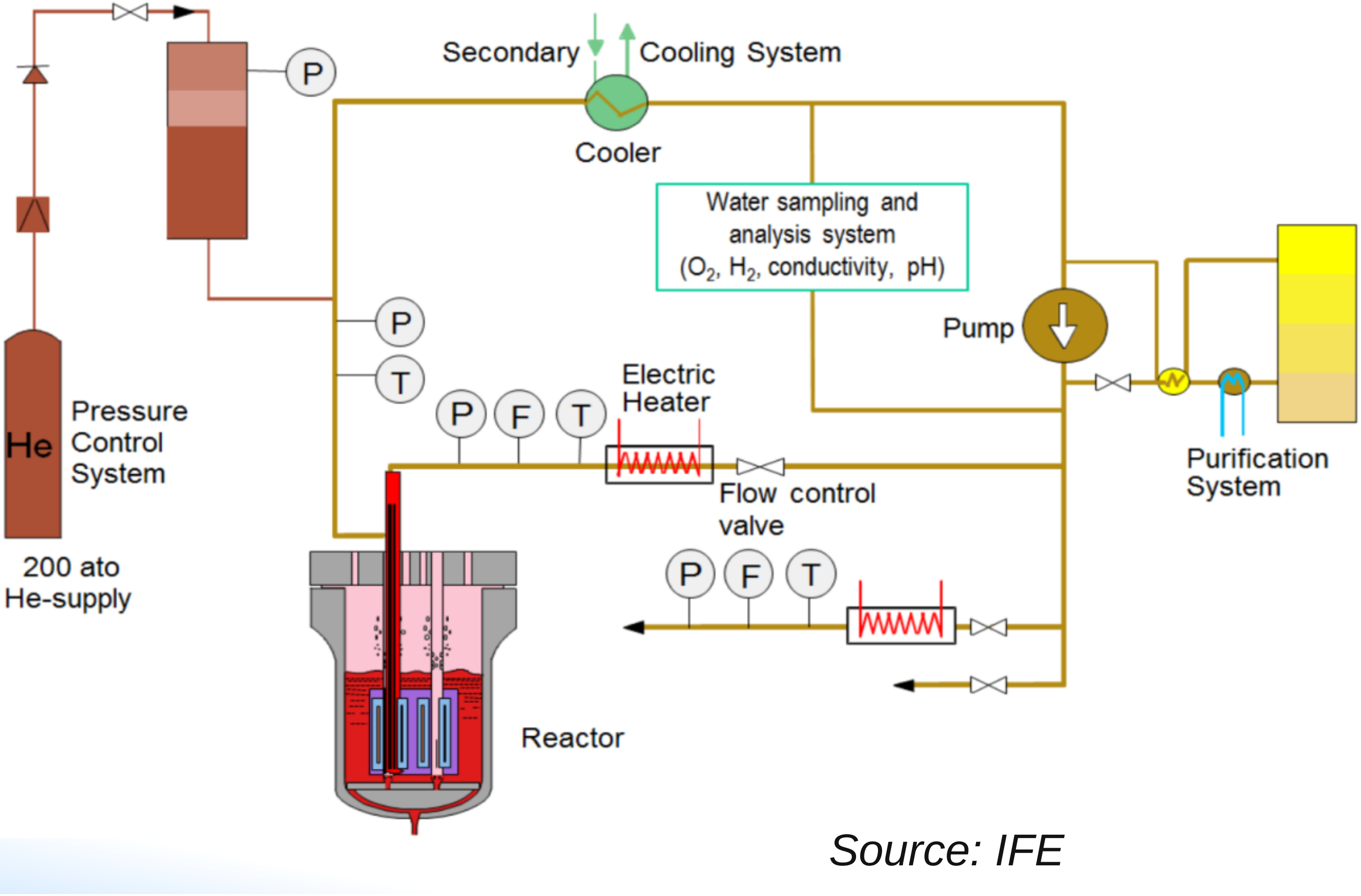
prediction

confirmation

Integral Test

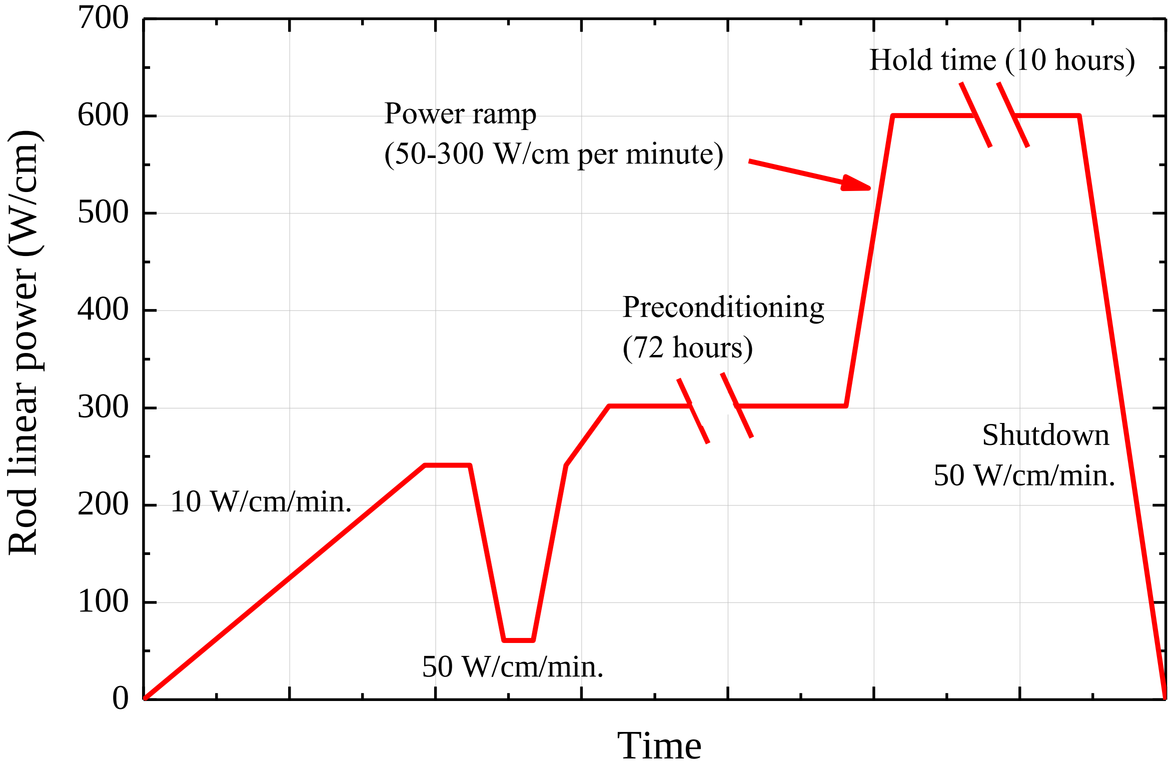
(HBWR) PRESSURIZED WATER LOOP

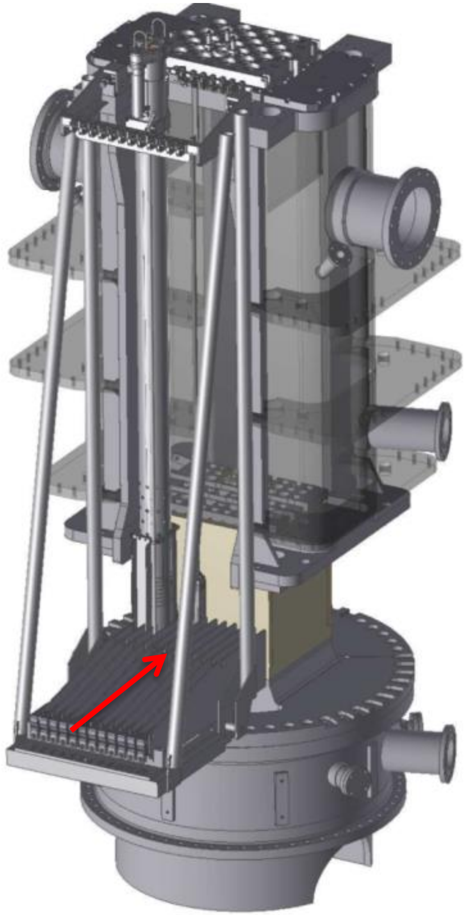
Schematic of a HBWR steady state loop system



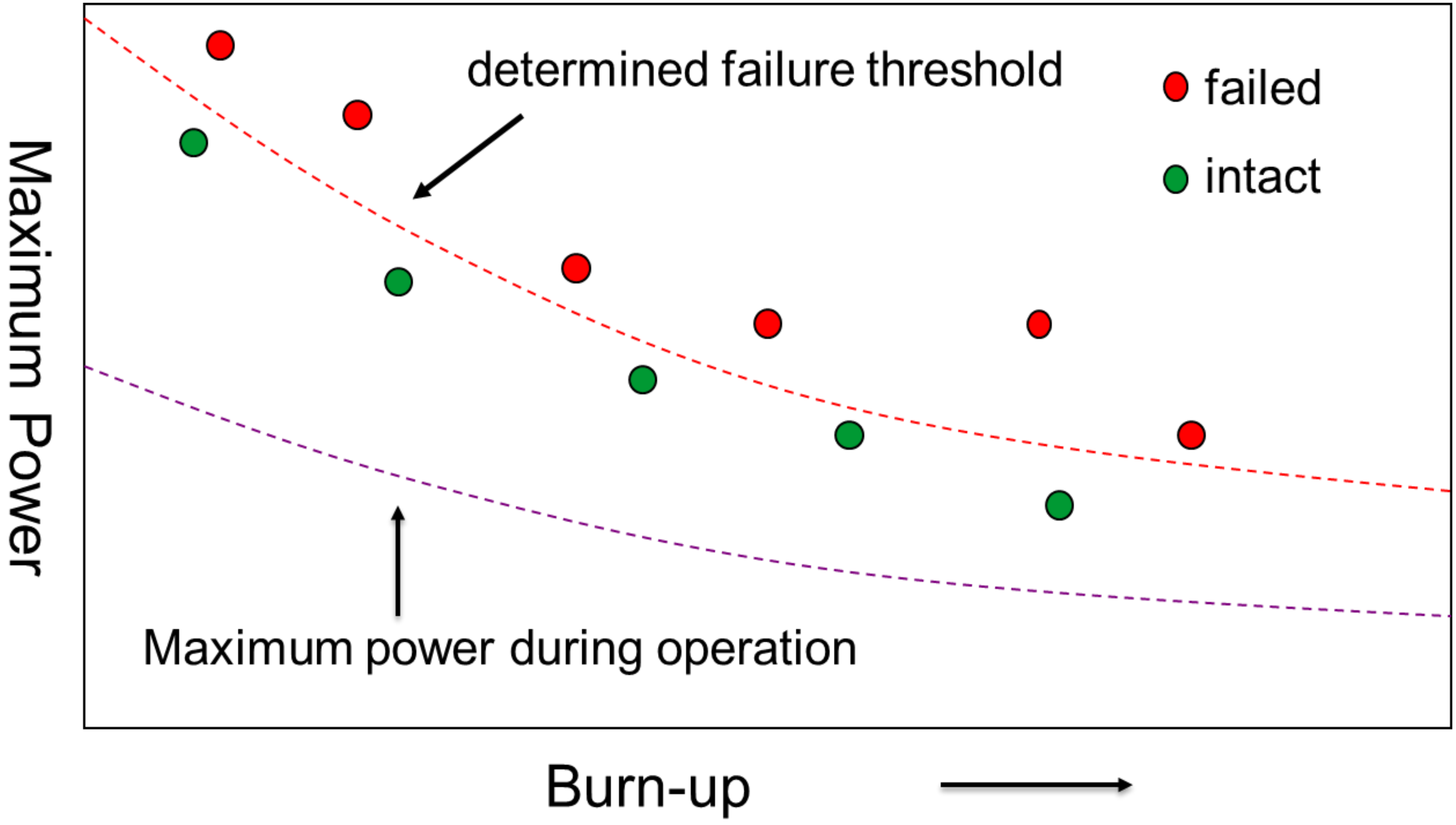
Source: IFE

EXAMPLE INTEGRAL TEST: POWER RAMP TESTING





EX: FUEL FAILURE IN RAMP TESTS



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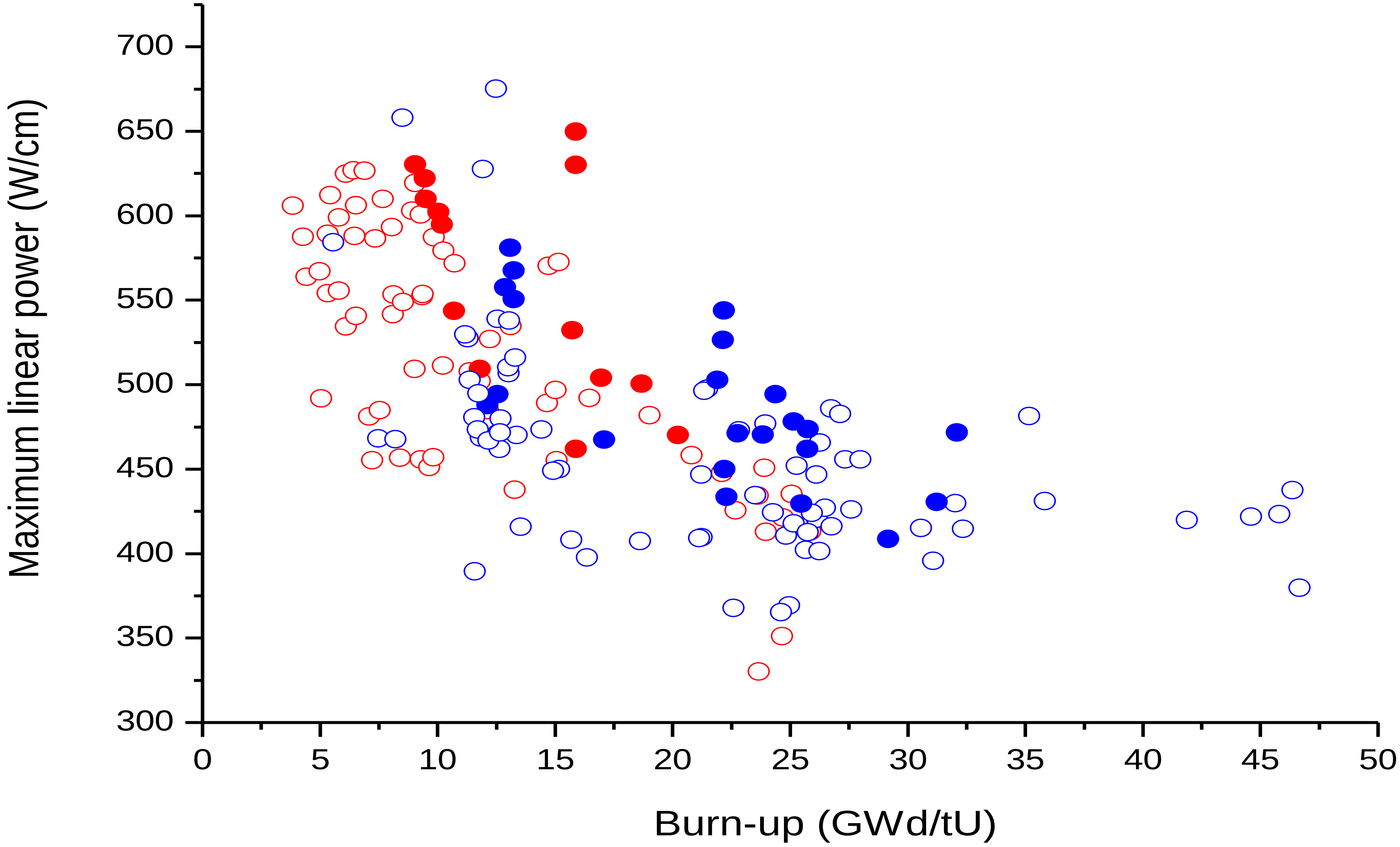
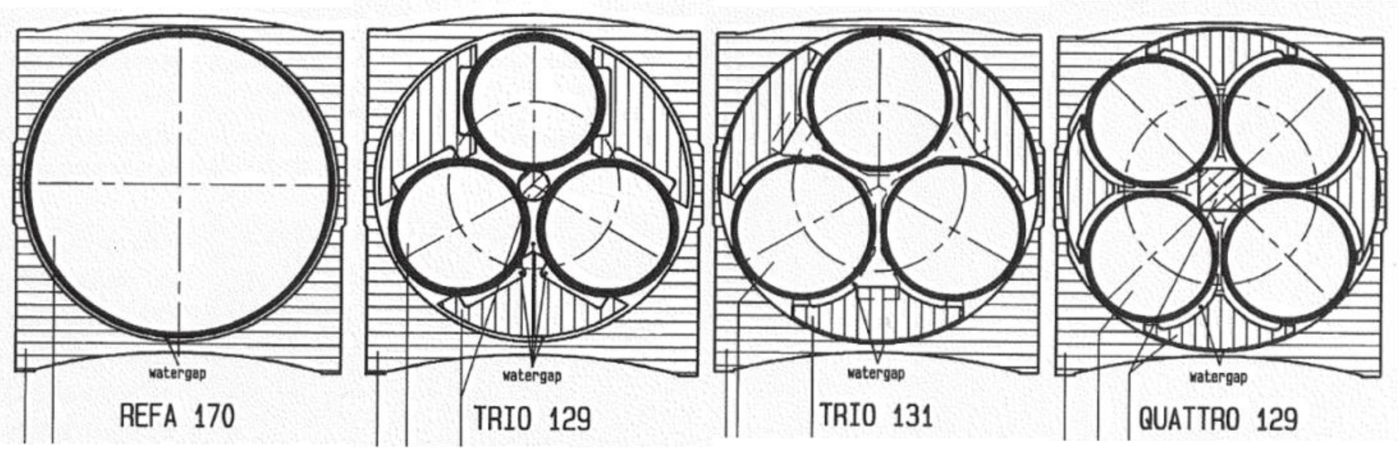
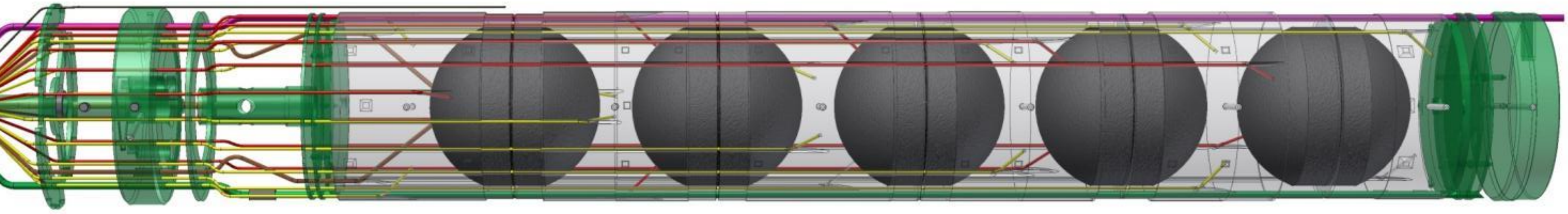


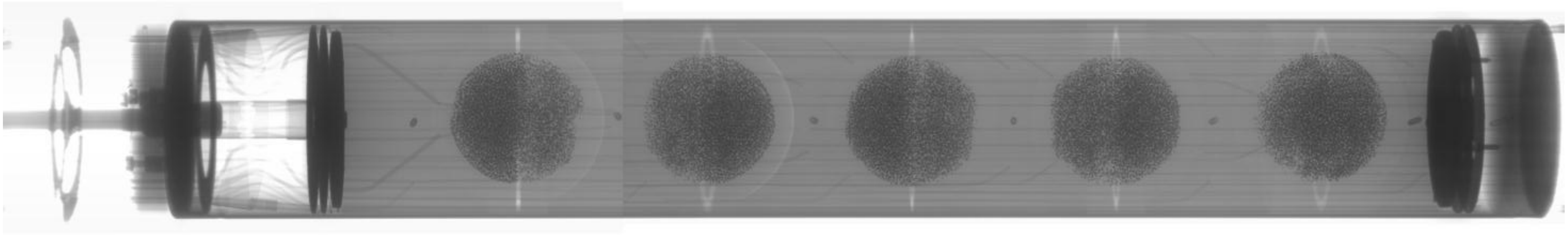
HFR STANDARD DRY CAPSULES



$\varnothing_{in} = 70$ mm	$\varnothing_{in} = 29$ mm	$\varnothing_{in} = 31.5$ mm	$\varnothing_{in} = 29$ mm
$\varnothing_{out} = 72$ mm	$\varnothing_{out} = 32$ mm	$\varnothing_{out} = 33.5$ mm	$\varnothing_{out} = 31$ mm

EXAMPLE 2: HTR PEBBLES





- Five HTR-PM fuel pebbles encased in graphite half shells
- Surrounded by a steel containment placed inside the HFR (REFA)
- **Question: release of activity from failed TRISO particles during irradiation?**

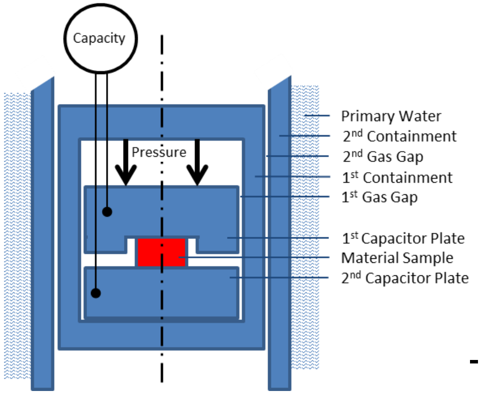
EXAMPLE 3: CREEP TEST

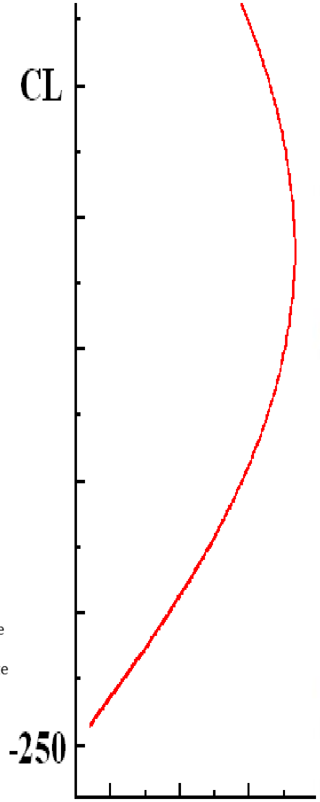
Design goals:

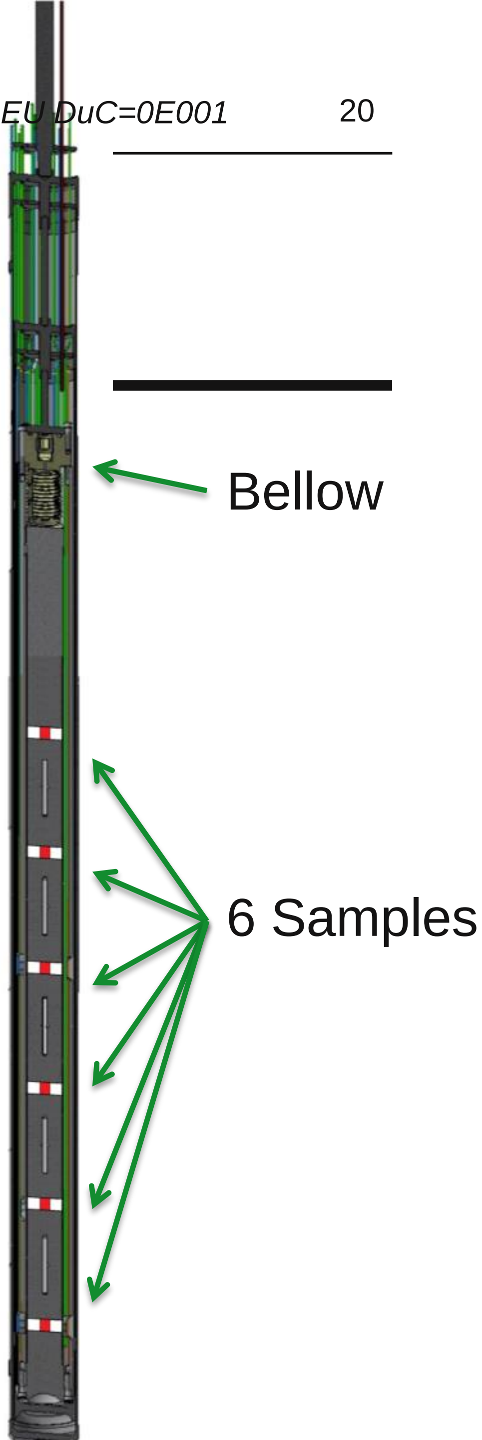
- Sample temperature tunable in the range of 400-1200°C
- Online control of sample stress in the range of 10-100 MPa
- Multiple samples to be individually measured simultaneously
- Online displacement measurement with an accuracy of <10 µm

Selected method: capacity measurements with parallel plates:

$$C = k\,\varepsilon_o\,(A / d)$$



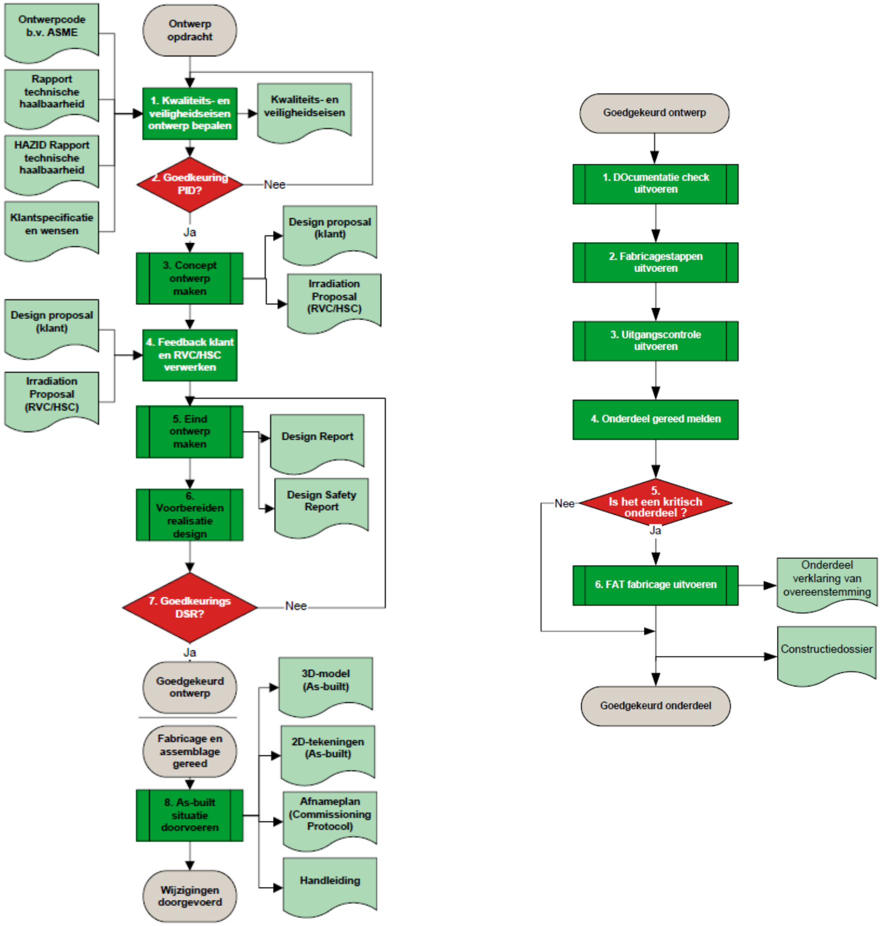




3. EXPERIMENT DESIGN AND REALIZATION

DESIGN PROCESS

- Starts with customer requirements.
- Concept design
- Final design
- Fabrication
- Assembly
- Commissioning
- Irradiation
- Decommissioning / dismantling
- Post irradiation examination
- Waste / data / archive material



Ontwerpcode b.v. ASME
Rapport technische haalbaarheid
HAZID Rapport technische haalbaarheid
Klantspecificatie en wensen
Ontwerp opdracht
1. Kwaliteits- en veiligheidseisen ontwerp bepalen
Kwaliteits- en veiligheidseisen
2. Goedkeuring PID?
Nee
Ja
3. Concept ontwerp maken
Design proposal (klant)
Irradiation Proposal (RVC/HSC)
Design proposal (klant)
Irradiation Proposal (RVC/HSC)
4. Feedback klant en RVC/HSC verwerken
5. Eind ontwerp maken
Design Report
Design Safety Report
6. Voorbereiden realisatie design
7. Goedkeurings DSR?
Nee
Ja
Goedgekeurd ontwerp
Fabricage en assemblage gereed
8. As-built situatie doorvoeren
3D-model (As-built)
2D-tekeningen (As-built)
Afnameplan (Commissioning Protocol)
Handleiding
Wijzigingen doorgevoerd

Goedgekeurd ontwerp
1. DOcumentatie check uitvoeren
2. Fabricagestappen uitvoeren
3. Uitgangscontrole uitvoeren
4. Onderdeel gereed melden
5. Is het een kritisch onderdeel ?
Nee
Ja
6. FAT fabricage uitvoeren
Onderdeel verklaring van overeenstemming
Constructiedossier
Goedgekeurd onderdeel

DESIGN PROCESS

- **Starts with customer requirements.**
- Concept design
- Final design
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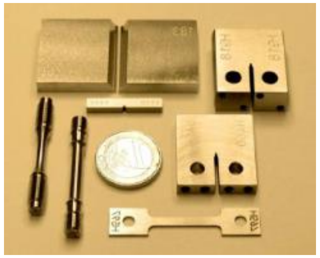
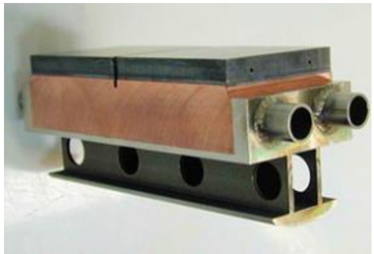
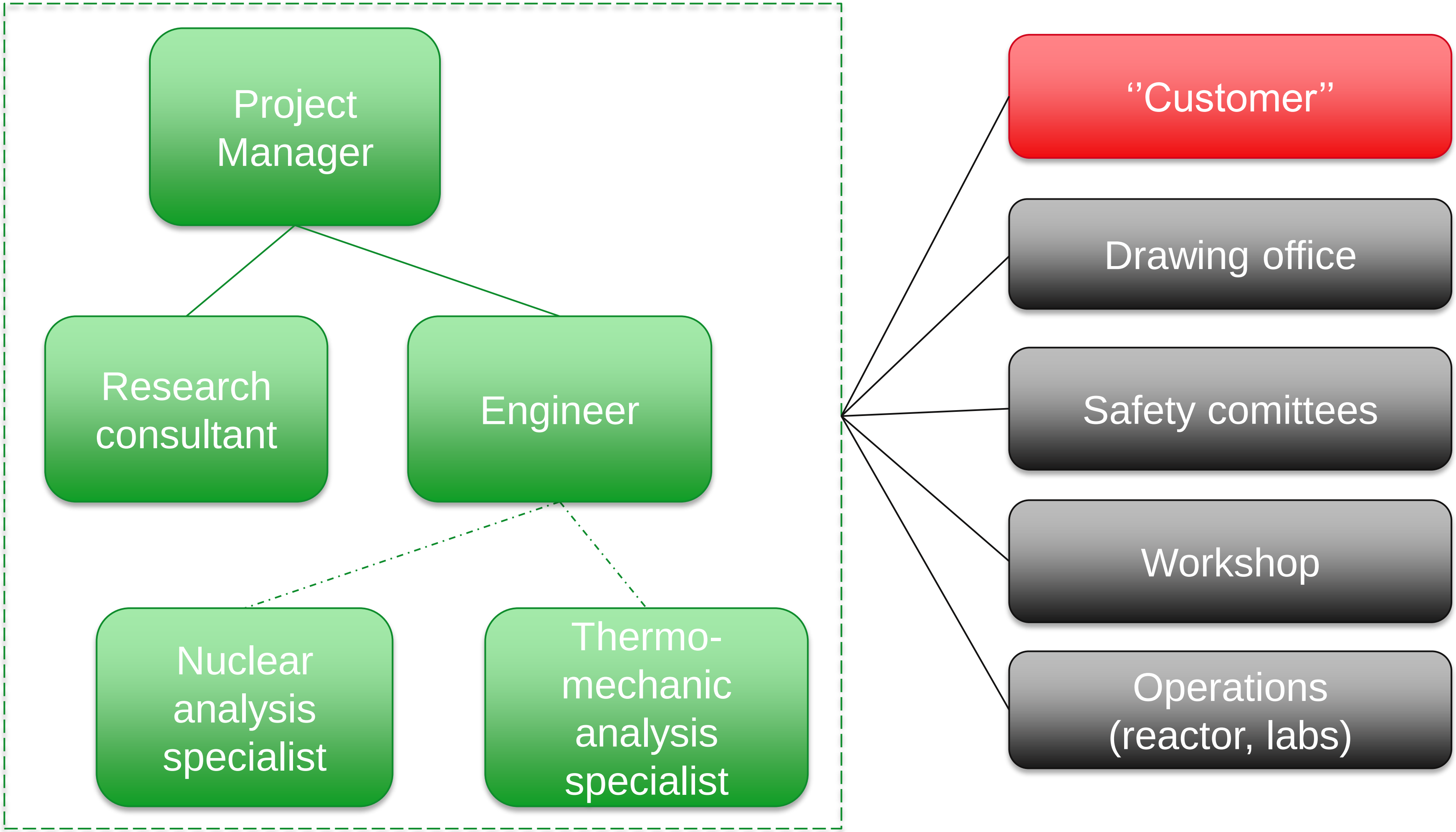
- **Specimen type, component qualification.**
- **Irradiation temperature**
- **Flux requirements**
- **Duration of the irradiation, DPA, burn-up**





PROJECT TEAM + ENVIRONMENT



Project Manager

Research consultant

Engineer

Nuclear analysis specialist

Thermo-mechanic analysis specialist

”Customer”

Drawing office

Safety comittees

Workshop

Operations (reactor, labs)

DESIGN PROCESS

- Starts with customer requirements.
- **Concept design**
- Final design
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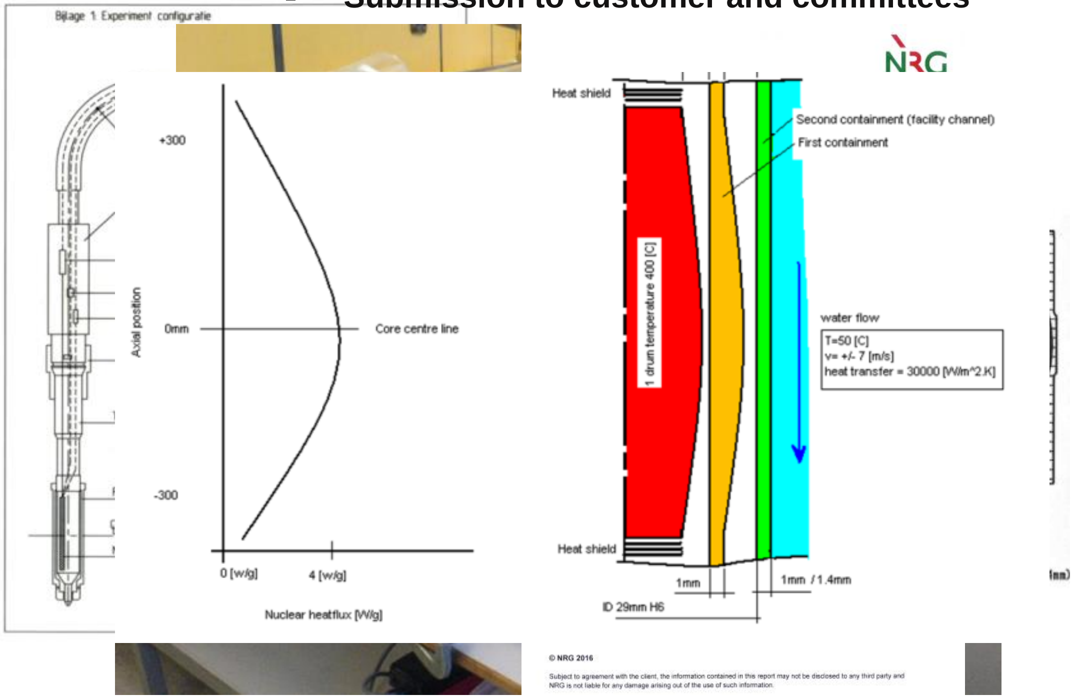
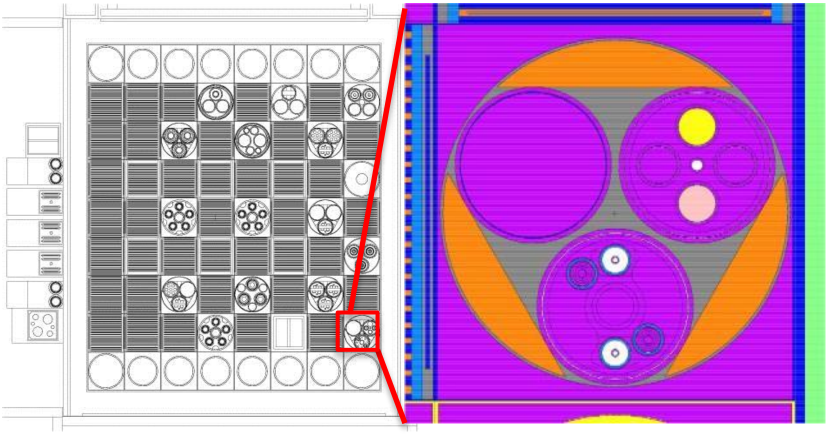
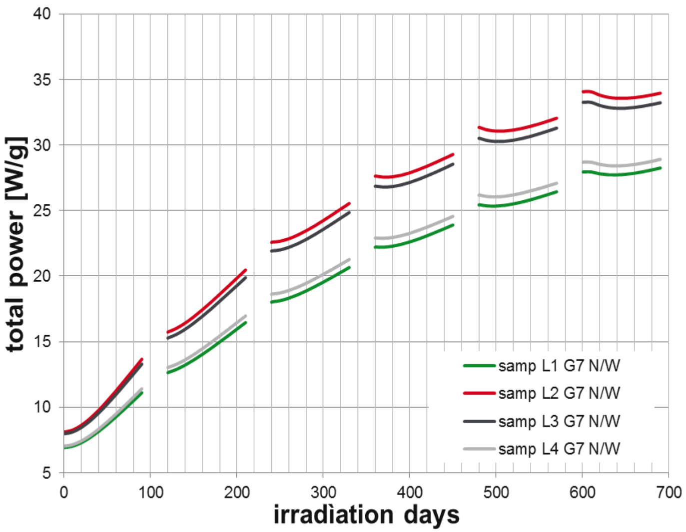
- **Standard facilities**
- **Design code, usually ASME**
- **Lessons learned earlier designs**
- **Material properties earlier irradiations**
- **Design report / proposal**
  - Initial analysis, TMA, TMH, MCNP, HAZID
- **Submission to customer and committees**



NUCLEAR ANALYSIS

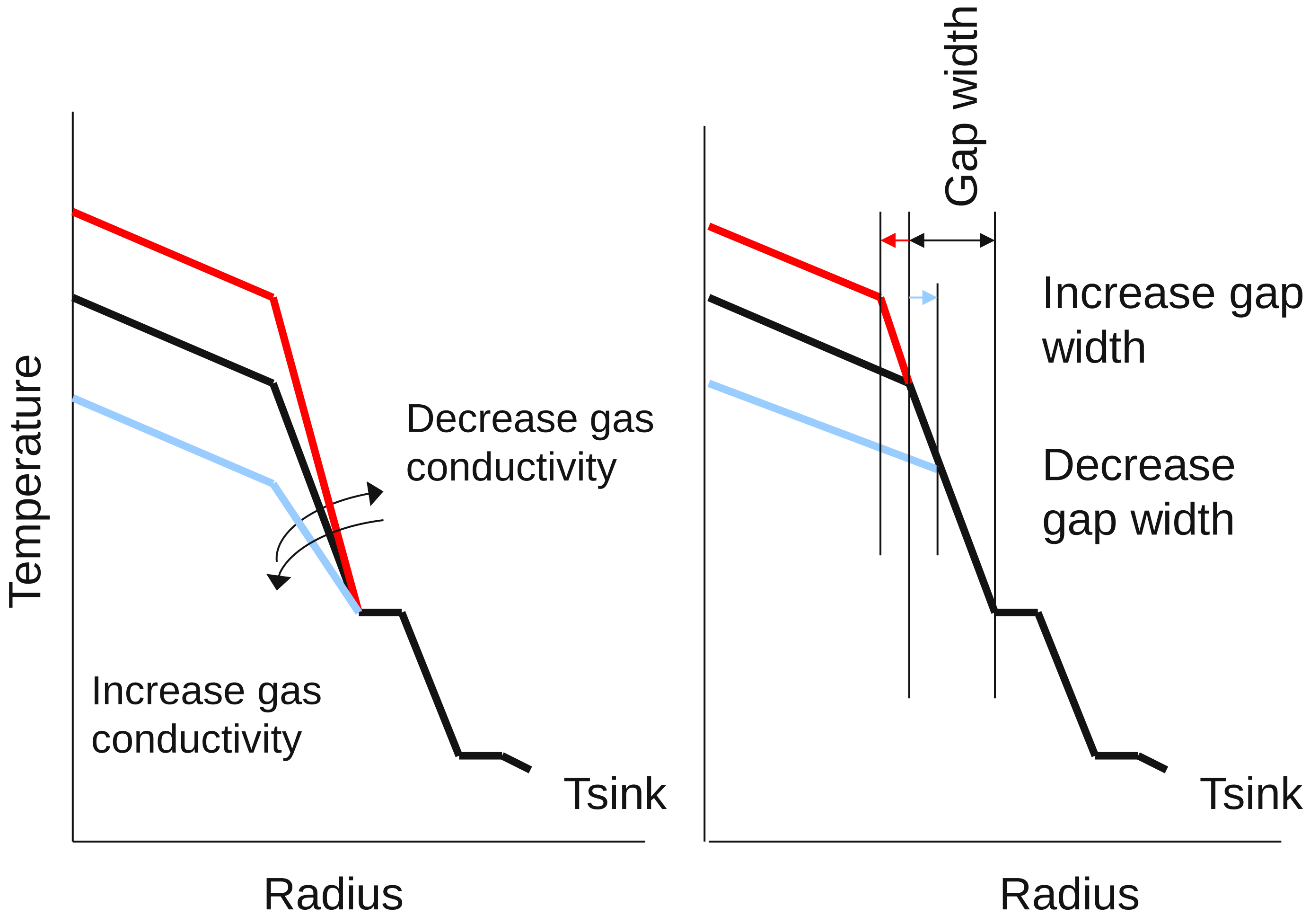
- MCNP/FISPACT is used to model the HFR core
    - Having an MCNP model for the reactor is needed for licensing
- An MCNP model is made for each experiment and placed inside the full core model
- Relevant output:
    - Neutron spectrum seen by the samples (dpa, transmutation rates)
    - Fuel power vs. time
    - Fuel and material compositions post-irradiation
    - Fuel and material activities post-irradiation
    - → Duration of irradiation





1-D THERMOMECHANIC ANALYSIS

- The heat sink temperature is provided by water cooling (~50 ºC).
- Temperature control at the HFR is performed with:
  - Gas mixtures
  - Gas gaps between the different containments.
  - Heaters are also possible but are usually omitted



DESIGN PROCESS

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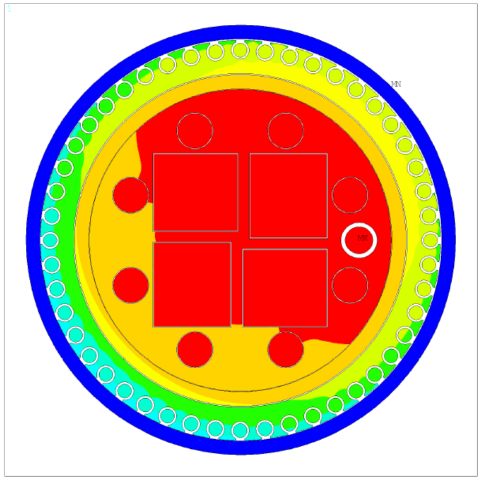
- **Design and Safety report.**
  - **According to ASME code.**
  - **Verification against customer requirements**
  - **Elaboration of analysis on 2D or 3D thermo-mechanical design, sensitivity studies**
  - **Safety assesment. Using HAZID, HAZOP or FMEA.**
- **Approval safety committees and**



ner

outcome

gs might need

s, radii etc.

rt.

DESIGN PROCESS

- Starts with customer requirements.
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- **Parts are (mostly) fabricated on-site**
- **For active specimens, assembly is performed in hot cell**
- **To comply with all safety, ASME and design requirements the parts and assemblies are accompanied with**
  - **Material certificates**
  - **X-ray inspection on critical welds**
  - **Dye-penetrant inspection**
  - **Proof pressure tests**
  - **Helium leak test**

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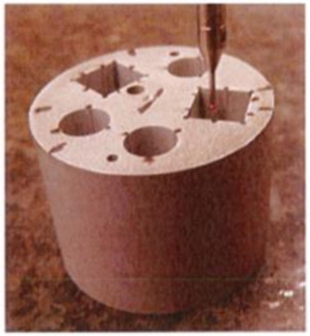
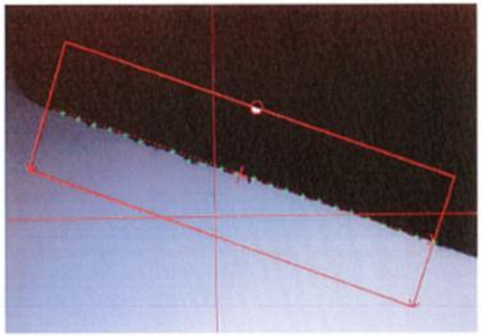
the FAT



Mitutoyo Strato 3D



Mitutoyo Quick Vision Pro

DESIGN PROCESS

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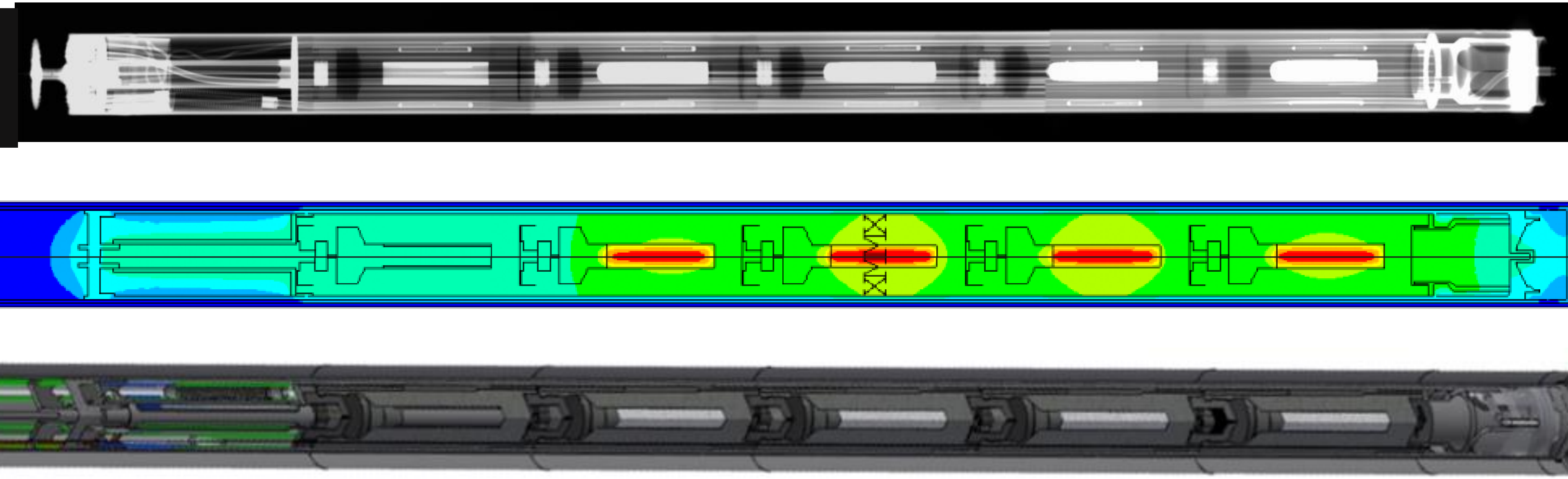
- **Commissioning at the HFR is safety and quality driven. It consists of:**
  - **Site acceptance tests,**
    - **Validation of instrumentation**
    - **Test fitting of the irradiation rig in a reference facility**
    - **Inspection of sodium level for sodium containing rigs.**
    - **SAT report**
    - **Approval for integration in the reactor hall.**

EXAMPLE:
X-RAY VS. MODEL VS. DRAWING



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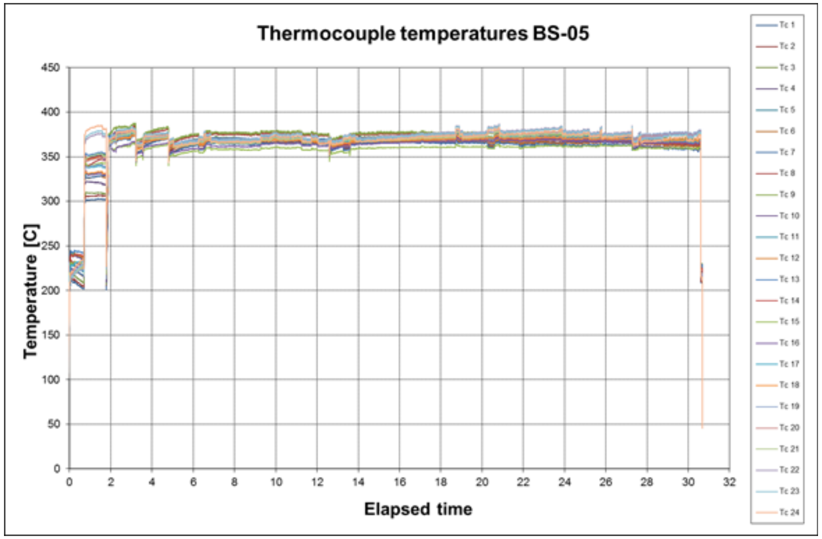
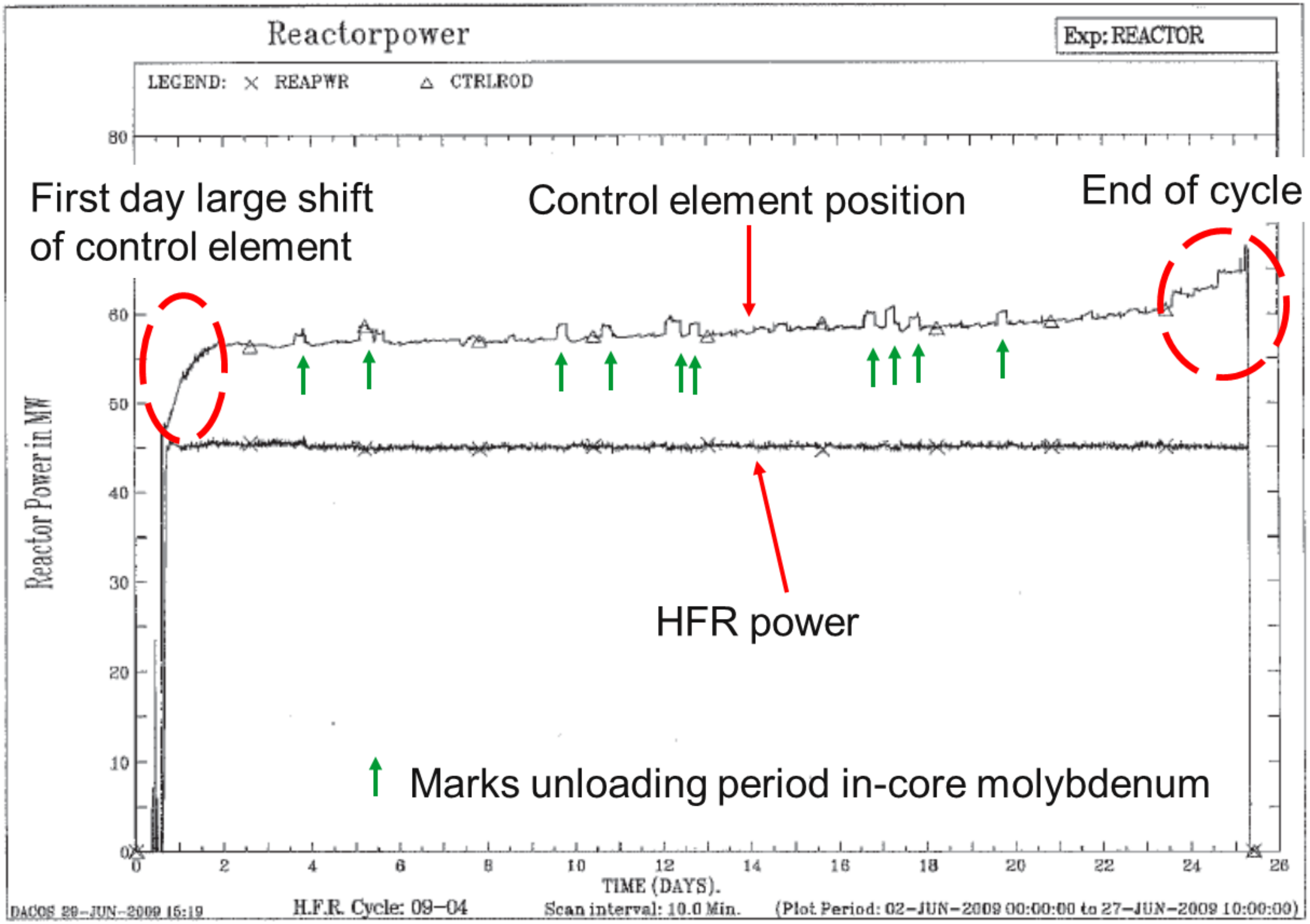
- **Before the start of each irradiation cycle checked-out.**
  - **Operator set and verify all SSS**
  - **Initial gas-mixtures are purged**
- **Irradiation**
  - **Gathering Data (temperature, gas composition, flux SPND)**



HFR CONTROL ROD MOVEMENT



First day large shift of control element

Control element position

End of cycle shift

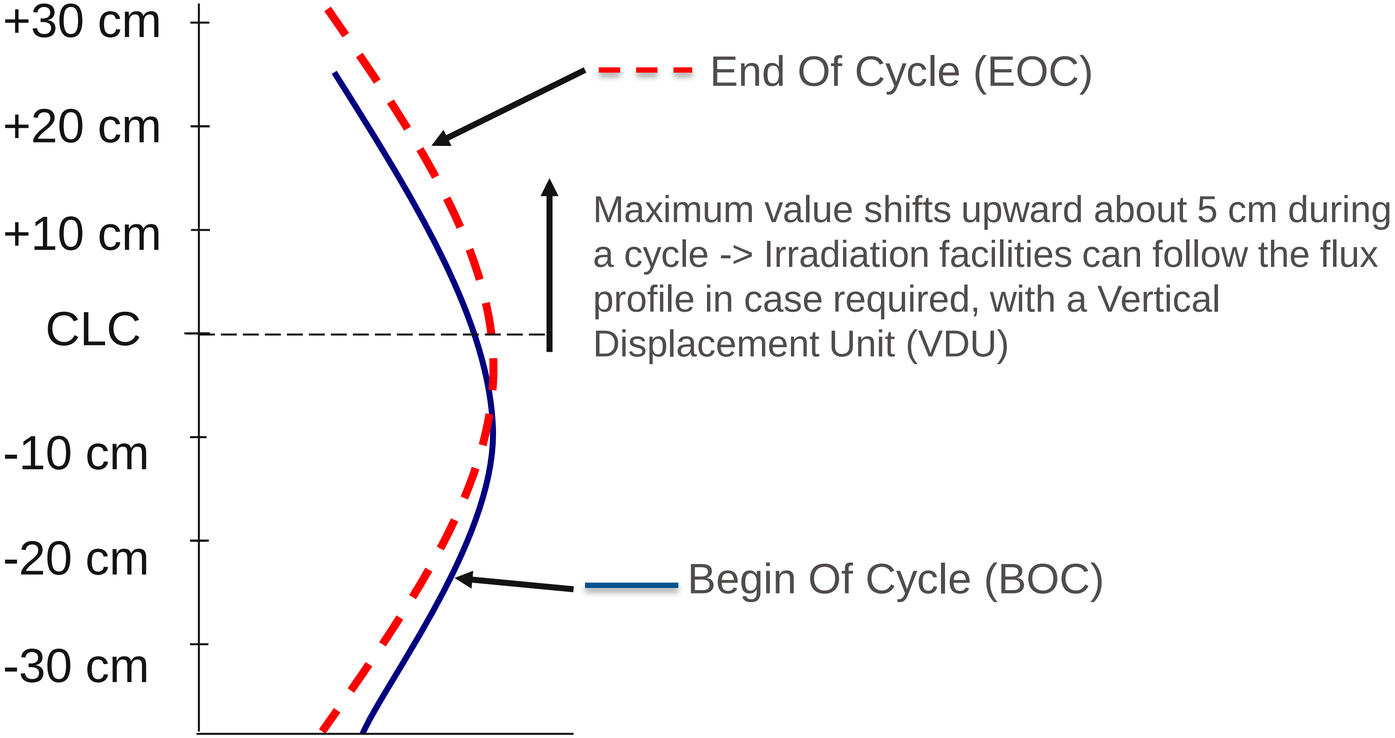
HFR power

↑ Marks unloading period in-core molybdenum

FLUX PROFILE BOC-MOC-EOC

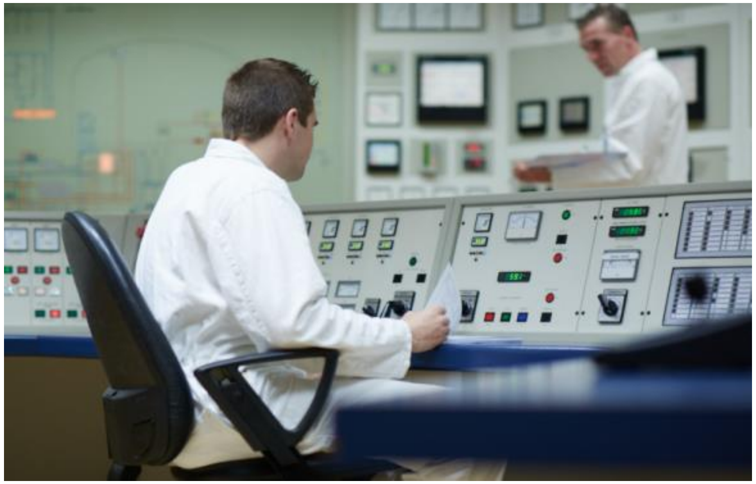
- An HFR cycles takes 30 days
- The flux buckle shifts upwards during a cycle → vertical displacement of experiments needed

The flux peak is just below core centreline (CLC)



Maximum value shifts upward about 5 cm during a cycle -> Irradiation facilities can follow the flux profile in case required, with a Vertical Displacement Unit (VDU)

ONLINE MONITORING



MONITORING OF BOUNDARY CONDITIONS

Online monitoring of boundary conditions for experiments is needed to reconstruct their irradiation history:

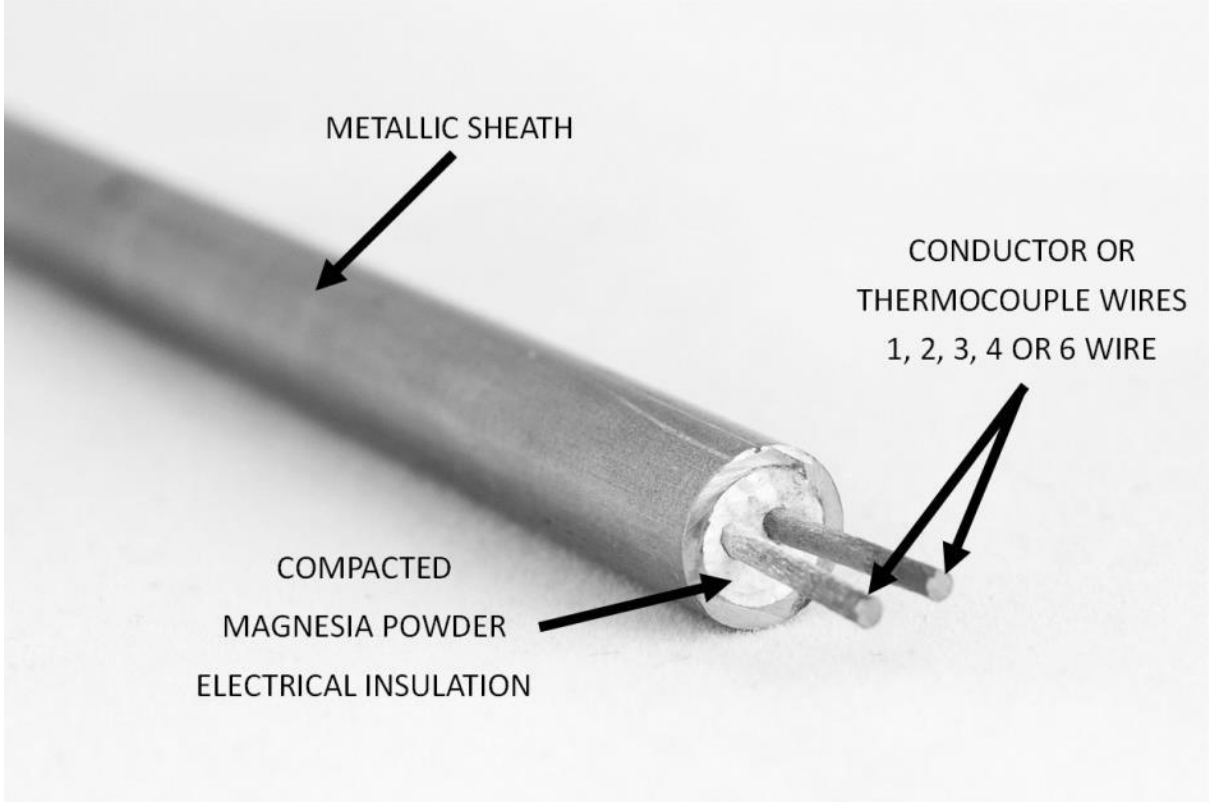
- Sample **temperature** (almost)
- Total **fluence** on sample (and neutron spectrum)
  - → *Burnup, final chemical state of the fuel…*
- Time-dependent **Flux** (=fluence rate) on sample
  - → *Fuel power / fission rate / fission gas production rate…*

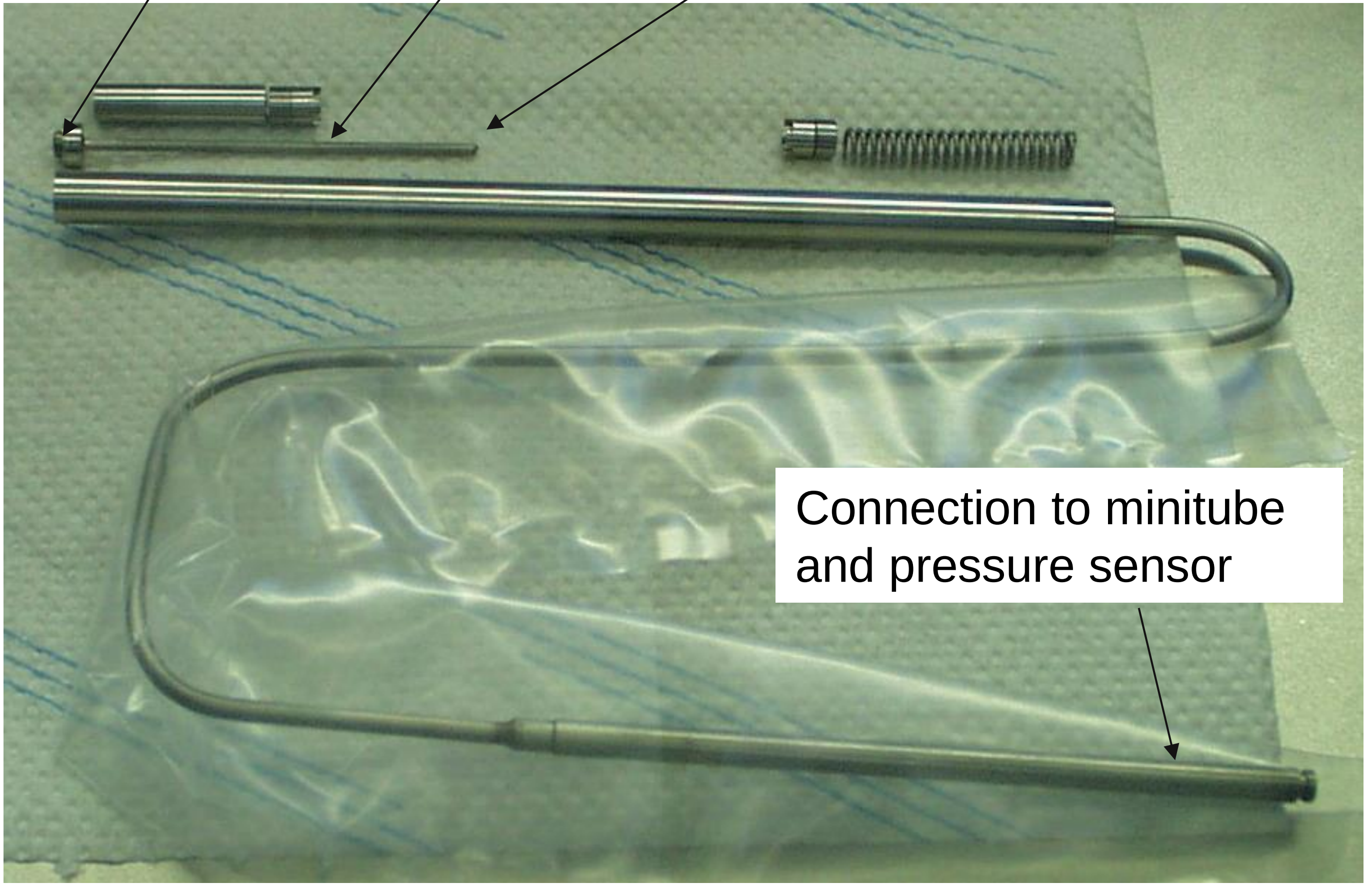
Therefore we add **thermocouples**, **fluence detectors** and **SPNDs** to experiments (as close as possible to the samples).

THERMOCOUPLES

Thermocouples

- Seebeck effect: electron movement from hot to cold in conductors.
- You always need two different conductors to measure a **difference**





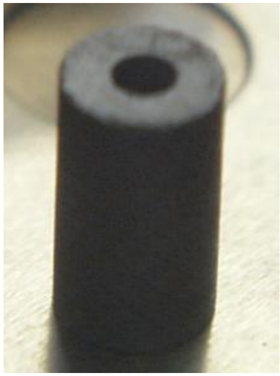
Insert thermo-couple

Open side

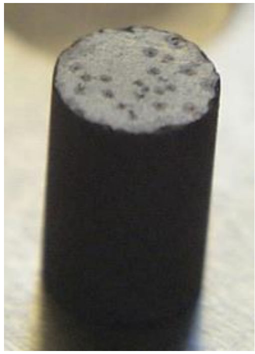
Niobium tube

Closed side

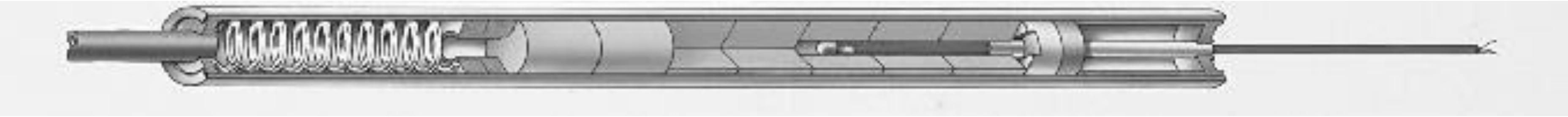
Connection to minitube and pressure sensor



Annular MOX



Solid MOX



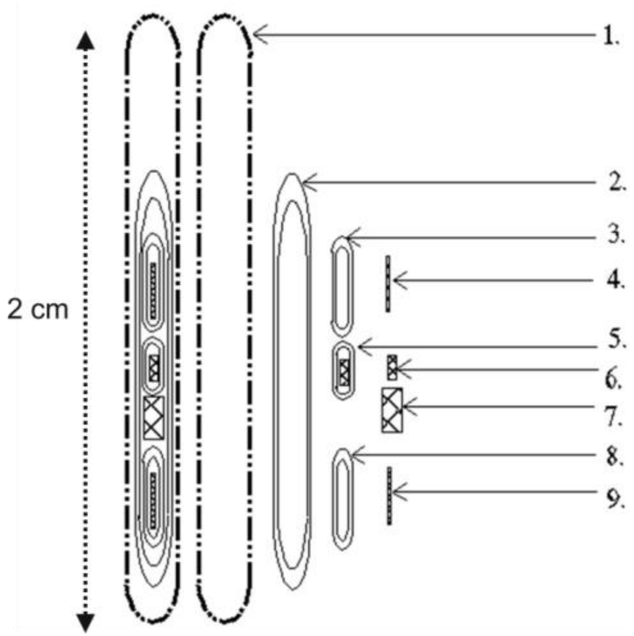
ACTIVATION MONITOR SETS AND GSW

Gamma Scan Wires (GSW) are simply stainless steel wiresplaced inside the experiment. A post-irradiation gamma scan reveals (at least qualitatively):

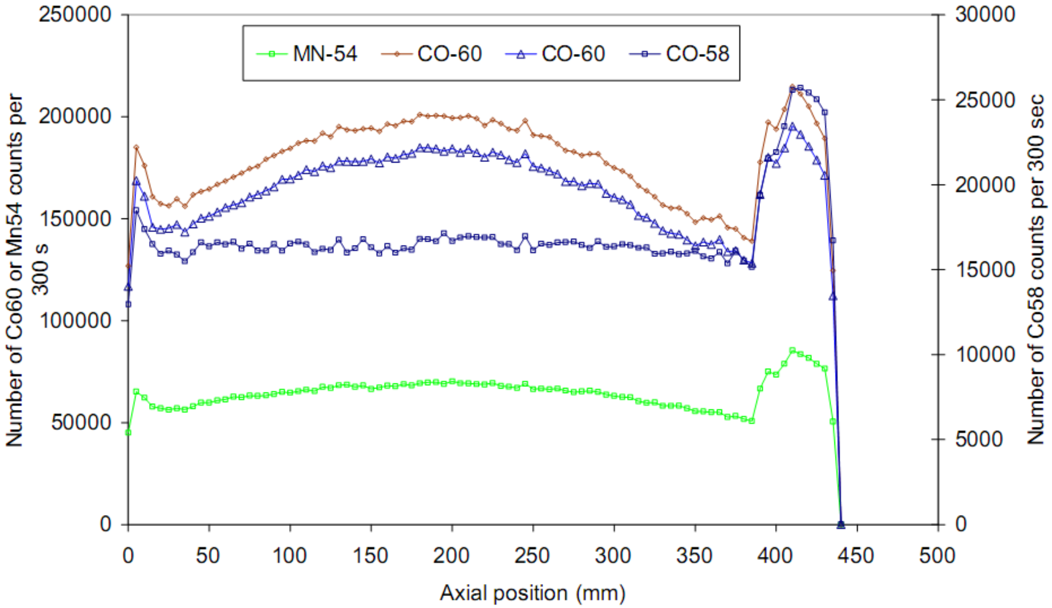
- ^{59}Co (n,γ) ^{60}Co: thermal fluence
- ^{54}Fe (n,p) ^{54}Mn: fast fluence

Neutron monitor sets are used to make gamma scan curves quantitative

Monitor set



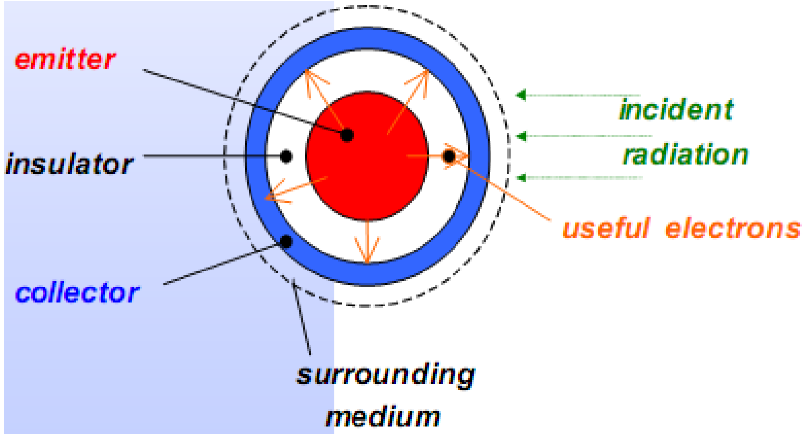
Gamma scan of a GSW

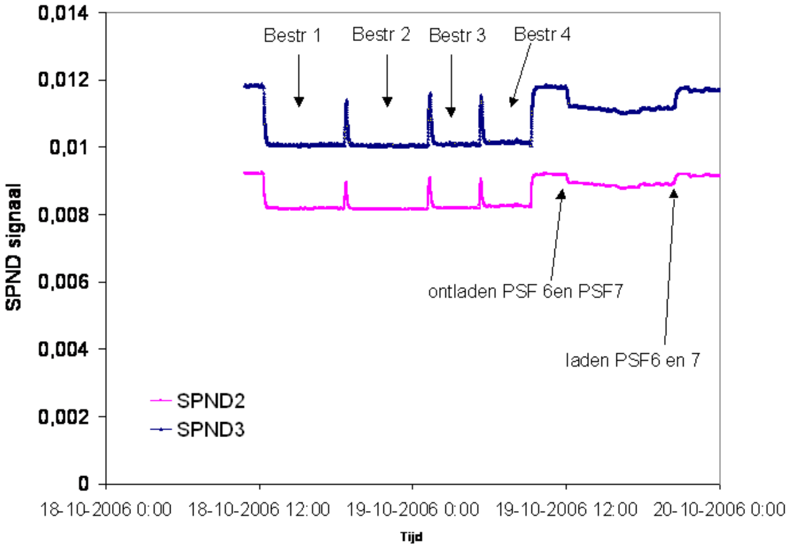


SPND

Self-Powered Neutron Devices

- Neutron absorption in the central emitter causes emission of electrons (β- radiation)

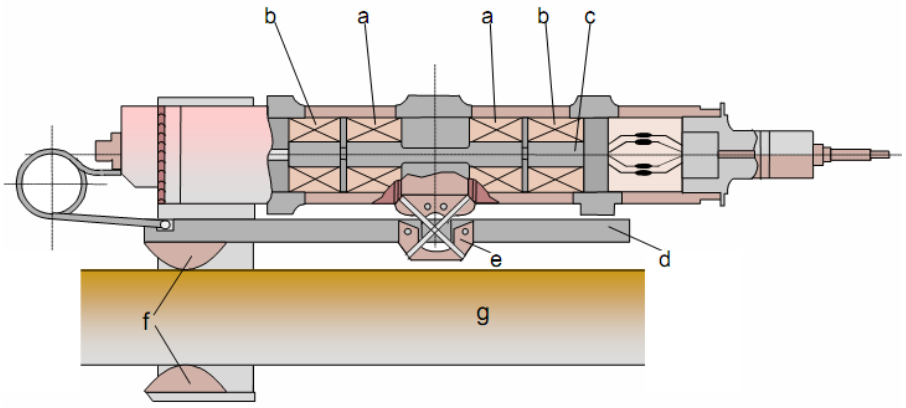


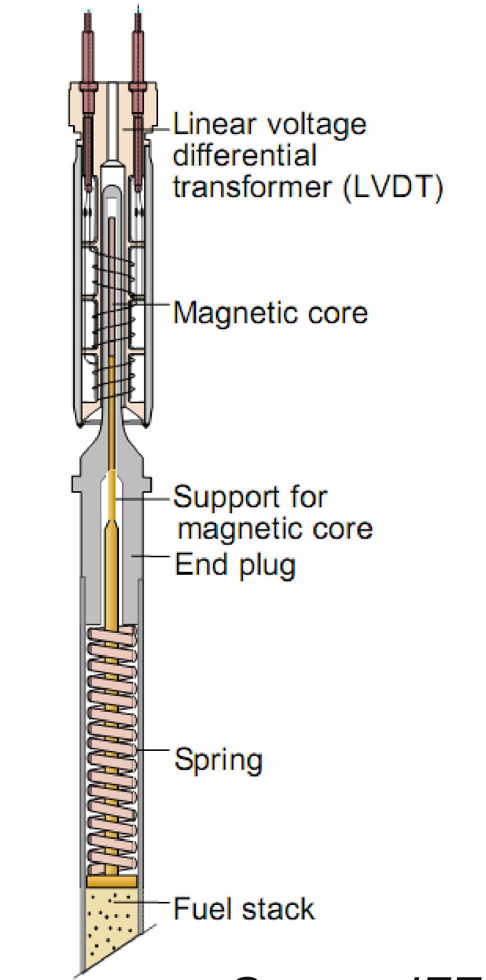


LVDT FOR DIMENSION CHANGE AND P

Linear Voltage Differential Transformer (LVDT)

- made for MTRs by IFE (‘Halden Reactor’)
- consists of wire coils wound around a magnetic stick
- an LVDT can be used to measure for instance:
  - Elongation due to thermal expansion or mechanical stress
  - Fuel swelling and creep
  - Pressure (if attached to a bellow)
- highly resistant to radiation
- LARGE!

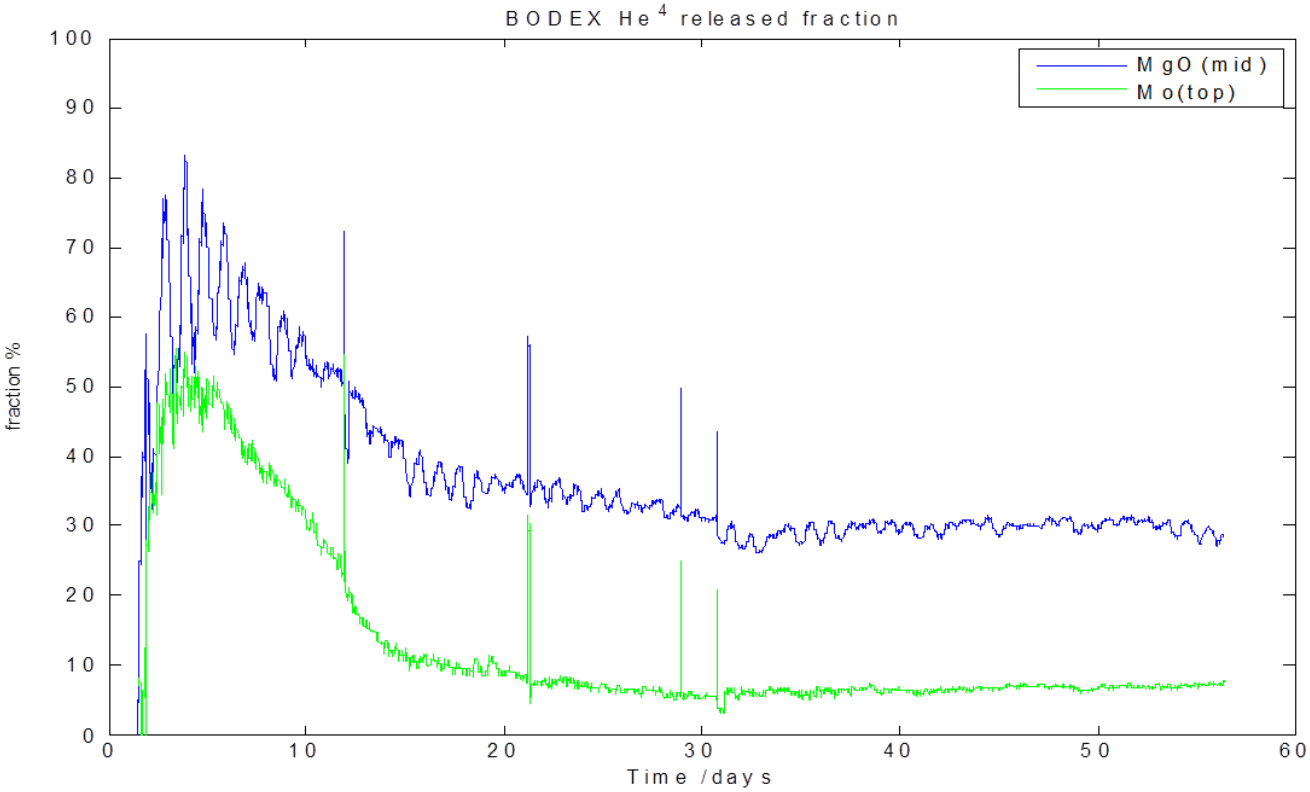




Source: IFE

ON-LINE PRESSURE MEASUREMENTS

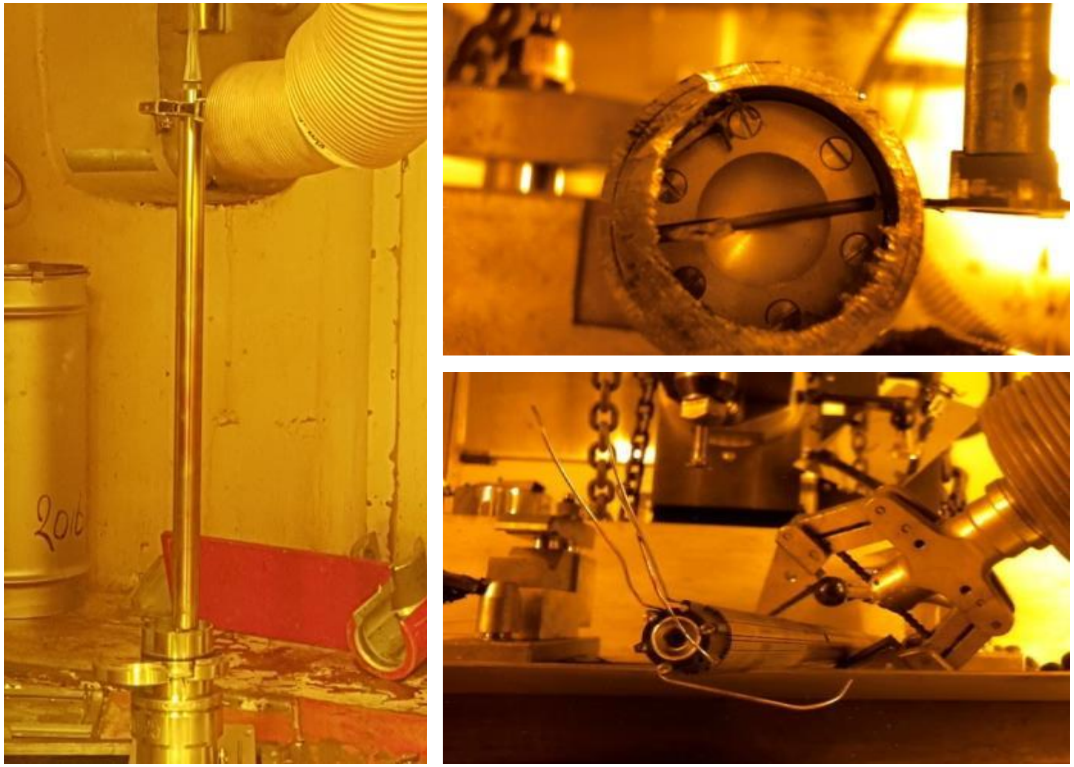
- Determine volume before irradiation (tricky!)
- Record temperature of the target continuously
- Assume that the temperature profile is constant



DESIGN PROCESS

- Starts with customer requirements.
- Concept design
- Final design
- Fabrication
- Assembly
- Commissioning
- Irradiation
- **Decommissioning / dismantling**
- Post irradiation examination
- Waste / data / archive material

- **In dismantling cell HFR**
- **Concrete cells HCL**



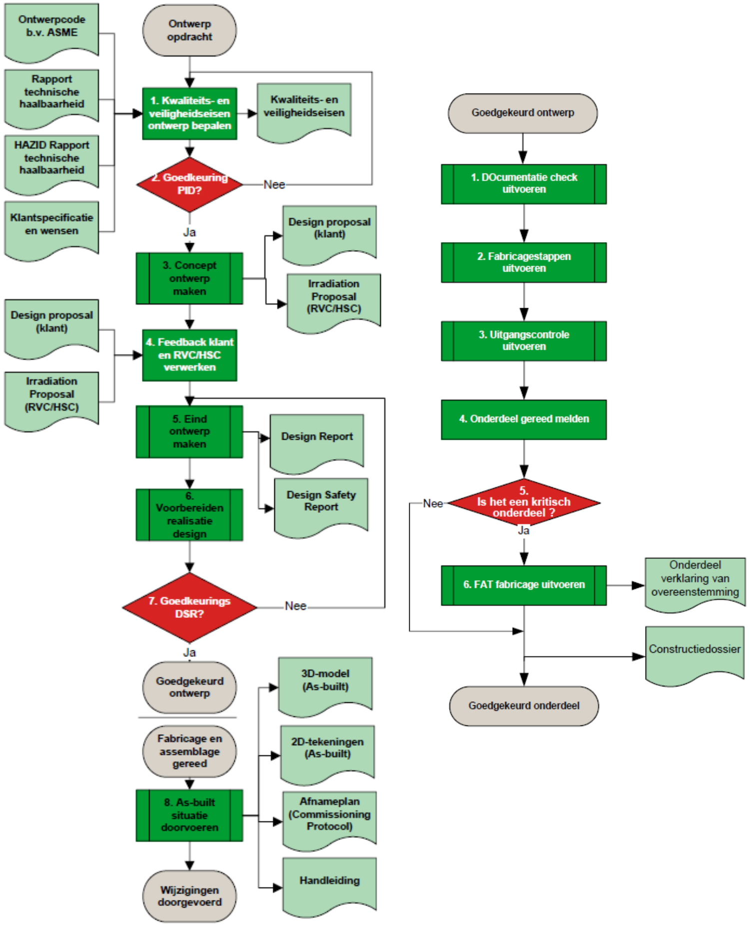
DESIGN PROCESS

- Starts with customer requirements.
- Concept design
- Final design
- Fabrication
- Assembly
- Commissioning
- Irradiation
- Decommissioning / dismantling
- Post irradiation examination
- **Waste / data / archive material**

- **The outcome of a program is usually**
  - **Data**
  - **Archive material**
  - **waste**

DESIGN PROCESS

- **Starts with customer requirements.**
- **Concept design**
- **Final design**
- **Fabrication**
    - As-build TMA
- **Assembly**
- **Commissioning**
- **Irradiation**
    - Initial irradiation TMA
- **Decommissioning / dismantling**
- **Post irradiation examination**
    - Gathering material properties
    - Post irradiation TMA
- **Waste**



LESSONS LEARNED

1. It is extremely important to define the 'research question' in detail upfront

2. Innovative experiments should start in the lab

3. The design of an irradiation experiment is a game of trade-offs:
   a) More safety barriers vs. more space
   b) More instrumentation vs. more samples
   c) More Redundancy vs. more information content
      i. For samples
      ii. For instruments
   d) Results (burn-up) faster vs. a better correspondence to ‘reality’

4. As a result, there is (and should be) some tension between project manager and researcher.