Unique Irradiation Rigs developed for the HFR Petten at the JRC-IE; details of LYRA, QUATTRO and Fuel Irradiation facilities

JRC-IE, Institute For Energy, Petten

L.Debarberis, B. Acosta, J.Degmova, A.Zeman, M. Fuetterer, E.D’Agata, P. Haehner
7 Institutes in 5 Member States:

**IE - Petten The Netherlands**
- *Institute for Energy*

**IRMM - Geel Belgium**
- *Institute for Reference Materials and Measurements*

**ITU - Karlsruhe Germany**
- *Institute for Transuranium elements*

**IPSC - IHCP - IES - Ispra Italy**
- *Institute for the Protection and the Security of the Citizen*
- *Institute for Health and Consumer Protection*
- *Institute for Environment and Sustainability*

**IPTS - Seville Spain**
- *Institute for Prospective Technological Studies*
Main items

- The HFR Petten
- Research reactor in the EU
- Recent facilities developed and operated in last decades
- Materials irradiation:
- Advanced fuels irradiation (e.g. HTR fuel)
- Other relevant facilities; e.g. neutron beams
- IDEAS FOR FUTURE RIGS
North-West - Holland

reclaimed from the sea

Petten 31 km
Alkmaar 13 km
Akersloot
Zaanse Schans 16 km
Amsterdam 41 km
North-West - Holland

- Petten 31 km
- Alkmaar 13 km
- Akersloot
- Zaanse Schans 16 km
- Amsterdam 41 km
1957 Beginning of the construction of the HFR.
1961 Provisional licence - first criticality.
1962 **Definitive licence for 20 MW operation**
   issued by municipal authorities - transfer the ownership of the reactor over to the European Commission.
1966 **licence adaptation for operation at max. 30 MW.**
1968 The EC becomes the licence holder - formal operator operation by ECN under contract.
1970 Entrance in force of the Nuclear Energy Act:
   Nuclear licences to be issued by National Authorities:
   Hindrance Act $\Rightarrow$ Nuclear Energy Act.
1970 **licence adaptation for operation at max. 50 MW.**
1984 **Replacement of the reactor vessel of the HFR:**
   The vessel renewal allows operation at least until 2015
1999 The HFR is operated by NRG
   under contract and responsibility of JRC-IE.
2003 Request for new HFR licence.
2005 **New licence granted to NRG** – EC retains ownership and responsibility for final decommissioning
The HFR today
### E.U. MTR Characteristics (P > 10 MWth)

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Power (MWth)</th>
<th>Utilisation: % Share</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nuclear</td>
</tr>
<tr>
<td>BR2</td>
<td>Belgium</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>HFR</td>
<td>Netherlands</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>LVR15</td>
<td>Czech Republic</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Halden</td>
<td>Norway</td>
<td>19</td>
<td>100</td>
</tr>
<tr>
<td>Osiris</td>
<td>France</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>R2</td>
<td>Sweden</td>
<td>50</td>
<td>45</td>
</tr>
</tbody>
</table>

- **FRM II in Garching (D) fully operational by mid-2004, but will face conversion from HEU to LEU by 2010**
- **Jules Horowitz Reactor project in France, but not before a decade**
The High Flux Reactor

- Light water cooled and moderated 45 MW$_{th}$ tank-in-pool multi-purpose materials testing reactor

- Low enriched uranium (~20% $^{235}$U) plate-type fuel elements with burnable absorber material and Be reflector

- Operated for 10 cycles per year (typical operating time 27 days per cycle)
• 20 in-core positions within a core arrangement of 9 x 9 positions containing 33 fuel elements, 6 control rods and 22 beryllium reflector elements

• 12 experimental positions outside the HFR vessel in the pool-side facility

• 12 horizontal beam tubes

• The HFR is mainly used for a) material/fuel irradiation experiments b) radioisotopes production c) industrial and medical research
Innovative Systems

Medical applications

Fundamental research

Nuclear Safety

Beam tubes

In-pile

Out of pile

Waste

Training

Structural and functional materials
## HFR Core Characteristics

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### PSFW

<table>
<thead>
<tr>
<th></th>
<th>1.22E+14</th>
<th>1.13E+14</th>
<th>8.70E+13</th>
<th>8.02E+13</th>
<th>5.42E+13</th>
<th>3.76E+13</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.32E+14</td>
<td>1.74E+14</td>
<td>1.03E+14</td>
<td>1.35E+14</td>
<td>6.23E+13</td>
<td>8.68E+13</td>
</tr>
<tr>
<td>3</td>
<td>1.50E+14</td>
<td>1.77E+14</td>
<td>2.92E+14</td>
<td>2.37E+14</td>
<td>7.45E+13</td>
<td>1.02E+14</td>
</tr>
<tr>
<td>4</td>
<td>1.42E+14</td>
<td>1.11E+14</td>
<td>1.32E+14</td>
<td>1.89E+14</td>
<td>5.75E+13</td>
<td>8.36E+13</td>
</tr>
<tr>
<td>5</td>
<td>1.55E+14</td>
<td>1.67E+13</td>
<td>2.01E+14</td>
<td>9.48E+13</td>
<td>8.26E+13</td>
<td>5.17E+13</td>
</tr>
</tbody>
</table>

### Beryllium

<table>
<thead>
<tr>
<th></th>
<th>1.13E+14</th>
<th>8.70E+13</th>
<th>5.42E+13</th>
<th>3.76E+13</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.03E+14</td>
<td>6.23E+13</td>
<td>8.68E+13</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.32E+14</td>
<td>6.07E+13</td>
<td>6.16E+13</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.74E+14</td>
<td>1.52E+14</td>
<td>1.78E+14</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.77E+14</td>
<td>1.50E+14</td>
<td>1.43E+14</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.35E+14</td>
<td>1.50E+14</td>
<td>1.43E+14</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.89E+14</td>
<td>1.52E+14</td>
<td>1.43E+14</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.37E+14</td>
<td>1.52E+14</td>
<td>1.43E+14</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.92E+14</td>
<td>1.52E+14</td>
<td>1.43E+14</td>
<td></td>
</tr>
</tbody>
</table>

### Fuel element

<table>
<thead>
<tr>
<th></th>
<th>4.37E+13</th>
<th>6.16E+13</th>
<th>6.07E+13</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.35E+14</td>
<td>1.35E+14</td>
<td>1.35E+14</td>
</tr>
<tr>
<td>3</td>
<td>1.74E+14</td>
<td>1.74E+14</td>
<td>1.74E+14</td>
</tr>
<tr>
<td>4</td>
<td>2.37E+14</td>
<td>2.37E+14</td>
<td>2.37E+14</td>
</tr>
<tr>
<td>5</td>
<td>2.92E+14</td>
<td>2.92E+14</td>
<td>2.92E+14</td>
</tr>
<tr>
<td>6</td>
<td>3.76E+14</td>
<td>3.76E+14</td>
<td>3.76E+14</td>
</tr>
<tr>
<td>7</td>
<td>5.42E+14</td>
<td>5.42E+14</td>
<td>5.42E+14</td>
</tr>
<tr>
<td>8</td>
<td>8.02E+14</td>
<td>8.02E+14</td>
<td>8.02E+14</td>
</tr>
</tbody>
</table>

### Control element

<table>
<thead>
<tr>
<th></th>
<th>9.48E+13</th>
<th>7.55E+13</th>
<th>3.74E+13</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8.70E+13</td>
<td>8.70E+13</td>
<td>8.70E+13</td>
</tr>
<tr>
<td>3</td>
<td>6.23E+13</td>
<td>6.23E+13</td>
<td>6.23E+13</td>
</tr>
<tr>
<td>4</td>
<td>1.32E+14</td>
<td>1.32E+14</td>
<td>1.32E+14</td>
</tr>
<tr>
<td>5</td>
<td>2.01E+14</td>
<td>2.01E+14</td>
<td>2.01E+14</td>
</tr>
<tr>
<td>6</td>
<td>4.11E+13</td>
<td>4.11E+13</td>
<td>4.11E+13</td>
</tr>
<tr>
<td>7</td>
<td>5.91E+13</td>
<td>5.91E+13</td>
<td>5.91E+13</td>
</tr>
<tr>
<td>8</td>
<td>8.98E+13</td>
<td>8.98E+13</td>
<td>8.98E+13</td>
</tr>
</tbody>
</table>

### Thermal Neutron Flux (Φthermal)

- Beryllium
- Fuel element
- Control element

### Fast Neutron Flux (Φfast)

- Beryllium
- Fuel element
- Control element
## HFR in-core reloadable irradiation capsules

### Table

<table>
<thead>
<tr>
<th>PSFW</th>
<th>1.78E+14</th>
<th>3.46E+13</th>
<th>1.52E+14</th>
<th>4.37E+13</th>
<th>1.92E+14</th>
<th>4.42E+13</th>
<th>1.42E+14</th>
<th>4.15E+13</th>
<th>1.53E+14</th>
<th>3.94E+13</th>
<th>1.55E+14</th>
<th>1.87E+13</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.37E+13</td>
<td>6.16E+13</td>
<td>1.50E+14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.22E+14</td>
<td>8.70E+13</td>
<td>5.42E+13</td>
<td>5.42E+13</td>
<td>6.70E+13</td>
<td>4.42E+13</td>
<td>1.78E+14</td>
<td>1.32E+14</td>
<td>6.07E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.20E+14</td>
<td>8.50E+13</td>
<td>5.20E+13</td>
<td>5.20E+13</td>
<td>6.50E+13</td>
<td>4.20E+13</td>
<td>1.60E+14</td>
<td>1.24E+14</td>
<td>5.91E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.30E+14</td>
<td>9.30E+13</td>
<td>5.90E+13</td>
<td>5.90E+13</td>
<td>6.90E+13</td>
<td>4.90E+13</td>
<td>1.70E+14</td>
<td>1.34E+14</td>
<td>6.34E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2.02E+14</td>
<td>7.70E+13</td>
<td>3.70E+13</td>
<td>3.70E+13</td>
<td>4.70E+13</td>
<td>3.70E+13</td>
<td>1.50E+14</td>
<td>1.15E+14</td>
<td>5.20E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.32E+14</td>
<td>8.82E+13</td>
<td>5.82E+13</td>
<td>5.82E+13</td>
<td>6.82E+13</td>
<td>4.82E+13</td>
<td>1.62E+14</td>
<td>1.26E+14</td>
<td>6.26E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.30E+14</td>
<td>8.90E+13</td>
<td>5.90E+13</td>
<td>5.90E+13</td>
<td>6.90E+13</td>
<td>4.90E+13</td>
<td>1.70E+14</td>
<td>1.34E+14</td>
<td>6.34E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1.32E+14</td>
<td>8.82E+13</td>
<td>5.82E+13</td>
<td>5.82E+13</td>
<td>6.82E+13</td>
<td>4.82E+13</td>
<td>1.62E+14</td>
<td>1.26E+14</td>
<td>6.26E+13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Diagrams

Various diagrams showing the layout of fuel elements (yellow), control elements (gray), and beryllium (green) within the reactor core.
- neutron fluence (matrix damage)
- impurities (late 60s: Cu & later P - L Steele and co-workers at ONRL)
- alloying elements
  - Ni identified ~10 y later
  - Today, indications on Mn, etc.
- thermal ageing, etc.
- Prediction models & formulas
- Surveillance programmes
Fluence, n cm$^{-2}$

DBTT SHIFT, °C

Precipitation (Cu)

segregation (P)

Direct matrix damage

TOTAL

Fluence, n cm$^{-2}$
Irradiation Damage: Understanding/Modelling/Best Practices

- Development of a semi-empirical model for irradiation effects on the embrittlement of reactor pressure vessel steels: P-Cu and Ni-Mn-Si effects included, as well as temperature and fluence rate effects
- Method successfully adapted for high chromium steels which are candidates for HTR and GEN-IV designs

Evidence for Cr stabilisation

higher Cr welds

Cr correction
JRC-IE Capital Facilities

High Flux Reactor (HFR)
45 MW Research Reactor

LYRA
LYRA Sample Holder
Conventional & Advanced Nuclear Fuels

HTR Fuel
- Coated particle (CP) retention of fission products (FP): quality control of CP fuel (licensing)
- FP transport in CP and fuel elements (FE): CP failure mechanisms modeling (CP, FE, and whole system)
- Optimization of CP design: extension of fuel limits (higher burn-up, temperature)
HTR Fuel In-Pile Performance: HFR-EU1 irradiation in HFR, qualification of German and Chinese fuel, measurement of fission gas release, papers, input to GIF/NGR projects
V/HTR fuel at high burn-up

Measurement of fission gas release during normal operation and simulated accidental transients

Irradiation test HFR-EU1 in the HFR Petten

KÜFA Facility at JRC-ITU
Medical radioisotopes

- Medical RI are grouped in two distinct categories:
  → Diagnostic RI 90 % of the worldwide market for medical RI
  → Cure/Palliative RI 10 % of the worldwide market for medical RI

- Diagnostic RI
  → Molybdenum-99 (of which the medical RI Tecnetium-99 is a decay product) accounts for more than 70% of the worldwide market for Diagnostic RI
  → HFR market share on Mo-99 worldwide is around 30% and in EU 51%

- Cure / Palliative RI:

- Only 6 major suppliers produce 92% of world market for medical RI:
  Nordion (45%), HFR (27%), SAFARI-1 (9%), BR2 (8%), OSIRIS (2%), FRJ2 (2%)

- Too little capacity in Europe to replace HFR on short or medium term
Radioisotopes production

HFR Production (% of total country needs)  Patients/year treated by HFR RI for diagnosis

In Thousands

Diagnosis purposes  Therapeutic purposes
Non-destructive testing — Standard test method for determining residual stresses by neutron diffraction

Essais non destructifs — Méthode normalisée de détermination des contraintes résiduelles par diffraction de neutrons

Reference number
ISO/TS 21432:2005(E)

© ISO 2005
An institutional research activity on residual stress analysis based on neutron diffraction and numerical modelling

HFR/HB4 - Large Component Neutron Diffraction Facility (LCNDF): First stress diffractometer in the world capable of handling 1000 kg components – here the specimen is a 600 kg mock-up of a reactor pressure vessel section

Lattice stresses derived in the centre of weld of a specimen
Ideas for future rigs - GIF

- Very High Temperature Reactor
- Supercritical Water Reactor
- Lead Cooled Fast Reactor
- Sodium Cooled Fast Reactor
- Gas Cooled Fast Reactor
- Molten Salt Reactor
Ideas for future rigs

- **SANS**

- **SCC loops in-pile**
  - up to SCW conditions
  - Pb loop (LFR)
  - gas loop (GIF)

- **High Intensity Positron beam**
- **Gamma facility**
- ............
Install at the HB3 beam tube, upstream of the SANS facility, a neutron velocity selector, which will replace the currently installed monochromator and will give access to high neutron wavelengths (5 – 20 Å).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cold Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>80-100K</td>
</tr>
<tr>
<td>Initial Gain factor</td>
<td>6</td>
</tr>
<tr>
<td>Cool power, W</td>
<td>800</td>
</tr>
<tr>
<td>Cold neutron flux (λ&gt; 4 Å) at sample 10^8 cm^2 s^-1</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Ideas for future rigs

- SANS

- SCC loops in-pile
  - up to SCW conditions
  - Pb loop (LFR)
  - gas loop (GIF)

- High Intensity Positron beam
  - Gamma facility
  - ..........
The HFR and PALLAS in 2015