HIGH FLUX REACTOR (HFR) PETTEN

CHARACTERISTICS OF THE INSTALLATION AND THE IRRADIATION FACILITIES
The Institute for Energy provides scientific and technical support for the conception, development, implementation and monitoring of community policies related to energy. Special emphasis is given to the security of energy supply and to sustainable and safe energy production.

As the Dutch centre of expertise in this field, NRG develops understanding, products and processes for the safe utilization of nuclear technology for energy production, for the environment and for health.
The High Flux Reactor

The High Flux Reactor (HFR) at Petten is owned by the Institute for Energy (IE) of the Joint Research Centre (JRC) of the European Commission (EC). Its operation has been entrusted since 1962 to the Netherlands Energy Research Foundation Nuclear Research and consultancy Group (NRG). Since February 2005, NRG became also the licence holder of the HFR.

The HFR is one of the most powerful multi-purpose research and test reactors in the world. Together with the hot cells of NRG at the Petten site, it has provided for over four decades, an integral and full complement of irradiation and post-irradiation examination services as required by current and future R&D for nuclear energy, industry and research organisations. Since 1963, the HFR has a recognised record of consistency, reliability and high availability with more than 280 days of operation per year. The HFR has 20 in-core and 12 poolside irradiation positions, plus 12 horizontal beam tubes.

With a variety of dedicated irradiation devices and with its long-standing experience in executing small and large irradiation projects, the HFR is particularly suited for fuel, materials and components testing for all reactor lines, including thermo-nuclear fusion reactors. In addition, processing with neutrons and gamma rays, research with neutrons and inspection services are employed by industry and research, such as activation analysis, boron neutron capture therapy (BNCT), neutron radiography and neutron diffraction.

In recent years the mission of the HFR has been broadened within the area of medical support through an important increase in the production of radio-isotopes, and through the start of patient treatment at the BNCT facility. In radioisotope production the HFR has attained the European leadership in production volume.

The current irradiation programmes at the HFR address areas in:

- R&D for nuclear fission energy, i.e. materials irradiation in support of nuclear plant life extension, transient testing of pre-irradiated LWR fuel rods containing UO2 or MOX fuel, testing of fuel and materials for innovative reactors.
- Transmutation studies of actinides and long-lived fission products for the heterogeneous and direct cycle. Studies in support of incineration of Pu.
- Support of R&D for thermo-nuclear fusion energy within the European Fusion Technology Programme, i.e. irradiation testing of candidate materials for the first wall and divertor protection materials, and testing of breeding blanket materials and sub-modules for reference blankets with tritium analysis.
- Processing with neutrons and gamma rays, investigation with neutron-based research and inspection services, i.e. radio-isotope production, activation analysis, boron neutron capture therapy, neutron radiography and neutron diffraction.
In October 2005, the conversion of the HFR from using highly-enriched uranium (U^{235}) fuel to low-enriched uranium (U^{235}Si) fuel started, with completion planned in May 2006. The conversion will have only a marginal impact on the reactor’s operation. The reactor has a total of 33 fuel rods and six control rods. The initiative to convert contributes to the worldwide efforts to limit the use of the proliferation sensitive highly-enriched uranium. The Dutch government issued a new nuclear energy licence for the reactor in February 2005, including the use of LEU fuel.

**Core management**
The new cycle length is 31.5 days with 28 full power days. The annual number of cycles is 10, which results in an optimum consumption of fuel.

The reload pattern of the core is optimised in order to maintain the optimal nuclear characteristics of the irradiation positions. In the figures below calculated neutron fluence rates and flux ratios are given.

\[
\Phi_{\text{Thermal}} = \text{thermal} \ (E < 0.625 \text{ eV}) \text{ neutron fluence rate (n/cm}^2/\text{s)}
\]

\[
\Phi_{\text{Fast}} = \text{fast} \ (E > 1.0 \text{ MeV}) \text{ neutron fluence rate (n/cm}^2/\text{s)}
\]

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**Table:**

<table>
<thead>
<tr>
<th>Beryllium</th>
<th>Fuel element</th>
<th>Control element</th>
<th>Thermal flux ratio</th>
<th>Fast flux ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
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<td>6.20E+13</td>
<td>5.91E+13</td>
<td>6.07E+13</td>
</tr>
</tbody>
</table>

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**Legend:**

- PSFW: Power Spectral Flux Weighting

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**Figure:**

- Beryllium
- Fuel element
- Control element
- Thermal flux ratio
- Fast flux ratio
Fuel for gas-cooled High Temperature Reactors (HTR) generally consists of kernels containing the fissile material, which is enclosed in typically 4 coatings to ensure its mechanical stability and leak tightness with respect to fission gas release. Thousands of the resulting particles are then embedded in a matrix material (typically graphite) and come in different shapes such as “pebbles” (typically 6 cm diameter spheres) or “compacts” (solid or annular cylinders of various dimensions). The core of a pebble bed HTR is a pile of pebbles whereas compacts will be inserted into graphite blocks that constitute a block-type HTR.

Several dedicated irradiation rig designs were developed and are in regular use in the HFR together with ancillary systems for gas supply and fission gas release analysis. These rigs are versatile in terms of size, number of accommodated fuel elements and temperature, and can thus be used for testing various types of fuel under various conditions. They can be coupled to available systems for gas supply and fission gas release analysis featuring different degrees of automation. The general aim of these experiments is the determination of fission gas release from the fuel elements, which has to remain at very low values even at high temperature and high burn-up. After the irradiation, the fuel can be additionally submitted to heating tests to simulate HTR cooling accidents and to determine up to which temperature the irradiated fuel would remain leak tight.

**Project BEST**

Equipped with optional water-cooling for high power densities, the irradiation rig can accommodate full size HTR pebbles or compacts with a maximum outer diameter of 65 mm in up to four independent capsules. Special irradiation rigs for testing samples such as coupons or compacts have been in use. The most recent experiment performed on pebbles is HFR-EU1bis (5 pebbles at very High Temperature Reactor conditions.

**Project HFR-EU1**

This is a new conduction-cooled design with double containment for up to five full-size HTR fuel pebbles enabling the simultaneous irradiation of two separate capsules at different temperatures. The design is amply instrumented with thermocouples, gamma scan wires, fluence detector sets and neutron flux monitors. These irradiation experiments are connected to gas systems allowing the temperature adjustment in the capsules by suitably mixing He and Ne in the gas gaps, and instrumentation for the analysis of fission gas release.

- A rather simple gas panel is available with semi-automatic He/Ne gas mixture adjustment for temperature control and with monitoring of fission gas release through on-line Geiger-Müller (GM) counters and batch-wise gamma spectrometry on gas samples. The installation is fully equipped with safety relevant alarm and interlock features.
- In addition, the new Sweep Loop Facility features fully automatic temperature control for three first containments and two second containments as well as on-line fission gas release with Geiger-Müller (GM) counters, sodium-iodine (NaI) detectors, and batch-wise gamma spectrometry on gas samples with minimized need for operator intervention and maximum versatility for future usage.
Knowledge of graphite behaviour under irradiation is crucial for the operation of gas-cooled reactors and the development of high temperature reactor technology (HTR/VHTR) and fusion. In the more than four decades of its operation, the HFR has contributed strongly to this development through irradiation of graphites, as well as ceramics and composites.

The facilities at the HFR allow high quality data to be collected and help provide a vital data platform on which to base future advanced reactor design and developments. Within the EU HTR project, NRG obtained the first irradiated data on new graphites and ensures that Europe maintains its lead in this important technological area.

Projects currently executed concern:

- Irradiation of core structures graphites at several temperatures in the range 850 to 1250 K with target doses up to 25 dpa_g. Rigs contain typically up to a few hundred specimens and are designed to load previously irradiated specimens.
- Irradiation of doped graphites and C & SiC base composite materials as candidate materials for special components in (V)HTR and fusion systems, at several temperatures in the range 650 to 1250 K with target doses up to 5 dpa_g.
- Piggy backs of specimens designed for modelling purposes, such as single crystals, fibres and matrices.
- Piggy backs of high temperature alloys, e.g. Cr and W.

High temperature irradiations are designed typically with high density materials for the specimen holders, avoiding the need for electrical heaters and enabling space allocation for specimens. Irradiation temperatures are controlled by the gas mixture technique. Multiple temperature levels in one rig are achieved through design features such as gas-gaps and thermal shields. Rig assembly procedures are compatible with the loading of previously irradiated specimens using subassemblies that can be filled in glove boxes or hot cells. The primary specimen environment is typically high purity helium (or neon) and purged if necessary. In pile operation is usually designed for pressure and flow control as well as impurity measurement.
Fuel testing at HFR

**Light Water Reactor fuel testing**

The main modes of testing Light Water Reactor (LWR) nuclear fuels in the HFR are:
- Ramp testing
- Steady state irradiation

Ramp testing is done in a reloadable LWR fuel rod irradiation device (BWFC). The BWFC-device is a capsule type irradiation device, which consists of:
- a pressurized, water-filled reloadable capsule, in which the power generated by the fuel rod is removed radially by subcooled boiling (on the fuel rod surface) and
- a capsule support, providing forced convection cooling of the capsule. In the capsule support the fuel rod power is measured using the thermal balance technique.

The BWFC device can also be used for steady state irradiations of LWR fuel rodlets. Steady state irradiations of all kinds of fuel rodlets (LWR fuel, fast reactor fuel, transmutation targets) can be made in sodium filled irradiation devices. These irradiation devices allow instrumentation with pressure transducers, central thermocouples and cladding thermocouples.

**Fast Reactor fuel testing**

Fast reactor fuel pins are being tested in stagnant sodium conditions, both inside the core and in the poolside facility. Tests in the core can be performed using cadmium or hafnium thermal neutron absorption shields. These shields give a significant hardening of the neutron spectrum during the test.

The poolside facility allows flexible power variations and temperature variations in order to simulate ramp conditions.

For both steady state and ramp test irradiations the fuel power is measured using the thermal balance method. The fuel cladding temperature is monitored at various axial positions using thermocouples that are placed in the sodium. Integrity of the pins can be checked during the irradiations.

**Materials Testing Reactor (MTR) fuel testing**

In the HFR there exists an extensive experience in testing of MTR fuel elements. These tests are used for the qualification of new MTR fuels. Due to the large number of full power days per year in which the HFR is operated, a high burn up can be achieved in a short period.

**Nuclear fuel testing under accident conditions**

In the 1970’s and 1980’s extensive tests were done in the HFR on the behaviour of nuclear fuel (both FBR and LWR) under accident conditions. This involved overpower tests, Loss Of Coolant Accident simulation tests and iodine redistribution tests. Despite the fact that these types of tests were no longer performed in recent years, at the HFR there exists a large interest in discussing the past experience and making an inventory of the current possibilities.
The excellent flux and availability characteristics of the HFR are reflected in the large number of irradiations performed on structural materials. Several tens of fission and fusion projects were recently completed or are running, involving up to a hundred rigs.

The effort on fusion materials is a major EU contribution to the detail design and building of ITER and the development of fusion power plant designs on the basis of experimental verification. Another major field is the support of the development of 4th generation (Gen-4) fission reactors aiming for advanced more irradiation resistant materials and materials processing.

The structural materials of concern comprise steels, both conventional stainless steel and advanced reduced activation steels, including oxide dispersed varieties, and special alloys such as Ni-base superalloys, chromium, tungsten and vanadium. The effect of neutron radiation on welds is prominently on the list of research targets.

The type of irradiation facility is tailored to the project needs in terms of specimen type and size, target dose and temperature(s), and environment. It further depends on the project objectives: screening of various materials or technologies (e.g. product form, composition, microstructure, welds & joints), or be focused on engineering data (e.g. loss-of-ductility, creep/stress-relaxation rate, residual toughness, conductivity).

Low temperature irradiation (~ 340 K) is typically done in SIWAS-type rigs or baskets with the specimen in direct contact with the primary coolant water, and using a full in-core position. Irradiations at temperature in the range 400 – 1200 K are typically performed in so-called TRIO or QUATTRO configurations, occupying respectively 1/3 or 1/4 positions. Internal channel diameters for specimen stacks are between 6 and 29 mm. Total stack heights are up to 400 mm. Rigs are generally instrumented with 12 to 24 thermocouples.

Specimen environment is either inert gas (He, Ne) or liquid metal (Na, NaK). Sodium-filled rigs are regularly chosen for their superior thermal characteristics.

- Advanced rig designs exist with multiple (2 to 8) sections at different temperature levels.
- For spectral tailoring a thermal neutron shield is integrated with the rig interior, using boron or cadmium. Specific specimen environments are created by static integration (e.g. PbBi) or dynamic (gas or liquid purge).
- Specimens can be stressed in-situ using bellow technology to obtain irradiation creep properties. Simple pre-strained assemblies in tensile or flexural mode are used to quantify irradiation stress-relaxation rates, being more representative for bolts.
- The proper allocation of thermocouples and neutron dosimetry sets allows accurate attribution of dose and temperature values to individual specimens.
Within the JRC Institutional Action SAFELIFE a series of activities on the evaluation and study of the issues related to materials and components ageing, neutron embrittlement and irradiation studies are carried out.

Dedicated irradiation rigs using state-of-the-art specialised irradiation technology have been developed for the HFR, in order to obtain high quality irradiation data to support modelling of radiation embrittlement.

The investigations are mainly aimed to improve forecasting life extension for Reactor Pressure Vessels (RPV), comparing also with RPV surveillance data, and the qualification of novel non-destructive examinations techniques to complement destructive methods.

A number of issues are also at present under investigation covering mainly:
- the detailed understanding of irradiation damage of RPV materials
- the role of neutron fluence and chemical composition (Mn-Ni, Cu/P interaction in particular)
- the influence of material structure, irradiation temperature, neutron field parameters, etc.

Several European Networks are co-ordinated within SAFELIFE; AMES, NESC, ENIQ, AMALIA, NET and SENUF.

In particular the AMES European Network (Ageing Materials European Strategy) started its activity in 1993 with the aim of studying ageing mechanisms and remedial procedures for structural materials used for nuclear reactor components. AMES carried out a large number of partnership projects using successfully the HFR and the LYRA rig in particular; including the recently successfully concluded PISA (Phosphorus Influence on Steel Ageing) and FRAME (advanced fracture mechanics for integrity assessment) projects. Concrete plans for a new facility to study in-pile SCC (stress corrosion cracking) for LWR reactor internals are under development.

Both Western- and Russian-based materials are involved in the various activities which are mainly undertaken as international co-operation projects with key players in the EU, Candidate Countries and NIS countries. The research is in a broad context of supporting the various ageing nuclear power plants in the EU and immediate neighbouring countries.

Important achievements have been obtained and are summarised in several published works in peer reviewed journals and proceedings of international conferences.
This activity aims at supporting progress towards improved performance and safety of European energy production systems through the standardisation and harmonisation of novel NDT methods and advanced mathematical modelling techniques and at providing a forum for training of young scientists.

To this end the following activities are carried out:

• Pre-normative research leading to drafting of a standard document for residual stress analysis based on neutron diffraction.
• Basic research pilot study on residual stress analysis of a single bead weld on a steel plate, including two experimental round robin exercises and one computational
• Parametric study aiming at the evaluation of stress relief heat treatment in welded Cr-Mo-V steel plates. Neutron diffraction, X-ray diffraction and computational round robin campaigns are carried out.
• Investigation of thermal ageing effects (micro-structure and defects analyses) on cast duplex stainless steels based on small angle neutron scattering (SANS).
• Mapping of residual stresses in piping, monolithic and dissimilar metal welds based on neutron diffraction. The data is used for the calibration of predictive numerical models.
• Assessment of novel repair weld methods for RPV cladding and primary circuit, based on residual stress evolution by neutron diffraction and numerical techniques.
• Residual stress investigations in C/C-SiC tubular specimens at room and high temperatures for the development of ultra-high temperature heat exchangers.
• Evolution of residual stress in irradiated steel welds for RPV internals.

An International Standard for “residual stress determination based on neutron diffraction” has been drafted by an international group of experts, unanimously approved by 24 European National Standards bodies.

HFR related facilities:

• Triple-axis spectrometer, using a pyrolytic graphite (PG) monochromator, neutron wavelength of 0.14 or 0.24 nm available, maximum fluence rate at specimen 3×10¹⁰ n/m²s, used for powder (structural) analysis in two-axis-mode
• Small Angle Neutron Scattering (SANS) Facility, using a 12 crystal PG double monochromator with 0.475 nm neutron wavelength, beam size at specimen 5 to 20 mm diameter, covering a scattering range of 0.05 to 4 nm¹, used for inhomogeneities and defects analyses
• Large Component Neutron Diffraction Facility - Residual stress diffractometer, adjustable wavelength ranging from 0.2 to 0.6 nm by PG double monochromator, maximum fluence rate at specimen ~10¹⁰ n/m²s, first neutron diffraction stress measurement facility in the world suitable for industrial components of up to 1000 kg
• Combined powder and stress diffractometer, neutron wavelength 0.257 nm with a maximum fluence rate at the specimen of ~10¹⁰ n/m²s, used for residual stress, texture, powder studies.
To carry out the European effort on fusion technology development, national research centres have joined forces in the European Fusion Development Agreement (EFDA). The EU has recently decided to build ITER, jointly with Japanese, Russian, Chinese, South Korean and American partners. This unique international development programme has a broader approach: it encompasses parallel activities to prepare for the fusion demonstration reactor.

The important role of the EU in the ITER initiative is also reflected in the HFR programme: HFR’s high versatility provides it with extremely relevant R&D capabilities for fusion power plant technology. The HFR contributes to the fusion technology development by providing experimental results utilising the HFR as the neutron source and partners’ hot cell laboratories to perform post-irradiation testing. The main areas of interest are the ITER vacuum vessel, the blanket development and the development of reduced activation structural materials: chromium steel and ceramic composites.

The irradiation of the blanket sections with lithium ceramic pebbles is not limited to post-irradiation testing, but it includes in-pile instrumentation for the operation of the ITER Test Blanket Modules. In this way the HFR provides valuable in-pile process data for blanket operations in ITER.

A wide variety of irradiation projects for fusion functional materials have been undertaken or are in progress. Controlled gas purge with on-line tritium monitoring and triple containment are key features for irradiation of tritium generating specimens.

- **EXOTIC**: Tritium production and release from Li-ceramics and up to 20% Li-burn-up (7.5-50% 6Li)
- **Pebble-Bed Assemblies**: thermo-mechanical behaviour of breeder pebble-beds: 300 Full Power Days up to 3% burn-up, at 850 to 1150 K.
- **HICU**: High dose irradiation of Li-ceramic pebbles, effect of tailored neutron-spectrum on pebble (stack) integrity, up to 20 dpa and 10% Li-burn-up.
- **HIDOB**: High dose Beryllium, effect of He-bubbles on tritium-inventory and pebble-bed behaviour. Four distinct temperature levels in one rig.
- **LIBRETTO**: Tritium production, extraction and release from liquid Pb-Li eutectic and tritium permeation under irradiation.
- **PARIDE**: Plasma facing material specimens, divertor and primary wall sub-assemblies.
Apart from specific facilities for molybdenum and silicon production, the HFR has several different standard facilities available for irradiation of radioisotopes. All facilities have their own characteristics. In general, a distinction can be made in reloadable and unreloadable facilities. The latter can only be loaded and off loaded during the shut down period.

**Reloadable Facilities**

- **TIRO (Thermal Flux Irradiation Device for Radioisotopes Production)**
  The TIRO facility has been developed to provide capacity for (short) irradiations in central positions in the HFR core. The aluminium holder consists of vertical tubes with irradiation possibilities for cans of 10 mm diameter and 50 mm length, 15 mm diameter and 25 mm diameter of 80 mm length. Also cans with length-multiples of 50 - 80 mm can be used. Six axial layers are available to place the capsules, which depending on the layer in the facility, gives a different flux.

- **RODEO (Rotating Device For Ir/Pt Production)**
  The RODEO facility is a rotating device, thus allowing for a uniform irradiation. Standard irradiation capsules of 25 mm diameter and lengths of 80 mm can be placed in a standard beryllium filler element in the I-row of the HFR, with or without a cadmium screen.

- **HIP (Herlaadbare Isotopen Productiefaciliteit – reloadable isotope production facility)**
  The HIP facility provides irradiation capacity for standard irradiation cans in the Pool Side Facility of the HFR. The aluminium holder consists of vertical tubes with irradiation possibilities for cans of 10 mm diameter and lengths of 50 mm, 15 and 25 mm diameters of lengths of 80 mm. Also cans with lengths of multiples of 50 - 80 mm can be used.

- **HFPIF (High Flux Pool Side Isotope Facility)**
  The HFPIF Facility can be installed in the Pool Side Facility to allow for irradiations of standard irradiation cans of 25 mm diameter. The facility can be placed and removed during reactor operation, so that it is available for irradiations at all times.

- **PRS (Pneumatic Rabbit System)**
  The PRS is arranged near the south wall of the vessel, just above centre line core. It is automatically operated. The polyethylene shuttle/rabbit has a diameter of 22 mm and an internal length of 100 mm. Irradiation times can be selected between a few seconds and one hour. A lead shielding is installed in the restraint structure to minimize the nuclear heating.

**Unreloadable Facilities**

- **IRIDIS (Iridium device for incore use)**
  The IRIDIS facility has been designed specifically for iridium production in position C5 of the HFR core. Iridium pieces of different sizes can be irradiated in any of six different axial layers of the facility with respectively specific fluxes.

- **FACHIRO (Facility with high Thermal Flux for Radioisotopes)**
  The FACHIRO facility has been designed for general radioisotope production in the HFR in-core positions. Due to the presence of a moderator around the facility and the minimum amount of structural material, the thermal fluence rate is relatively high.

With these facilities the HFR provides a wide range of irradiation capabilities. Irradiations can be requested at the Radio Isotopes Production Team.
Physical and chemical characterisation
Apart from production facilities for radionuclides, NRG also manages facilities for manipulation and physical, chemical and analytical characterization of irradiated targets. Second to safety, Good Manufacturing Practice is the leading principal here.

Physical characterisation of targets is taken care of in the Fermi Laboratory where NRG specialists operate 10 Gamma-Ray Spectrometers, all tuned for specific applications. Furthermore, radiochemical laboratories are dedicated to chemical manipulation of radioactive materials. These processes both serve for production, purification and analytical purposes. The laboratories house several liquid chromatography, mass spectrometers, dedicated gamma ray spectrometers and series of glove boxes. One laboratory serves as a clean laboratory for production of active pharmaceutical ingredients. With these facilities NRG is able to characterise the isotopic, radionuclide, elemental and chemical composition of radioactive solids, liquids and gasses.

All these facilities generate the possibility for NRG to construct a nearly complete tailor made production process, including physical and chemical characterization, once a target has been irradiated.

### Selection of medical isotopes produced in HFR

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life/days</th>
<th>Use</th>
<th>With/for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molybdenum-99/</td>
<td>2.75/0.25</td>
<td>Diagnostic</td>
<td>Cancer: Lung, brain, heart thyroid and kidney function / infections / bone diseases</td>
</tr>
<tr>
<td>Technetium-99m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodine-131</td>
<td>8.04</td>
<td>Therapeutic</td>
<td>Thyroid disease</td>
</tr>
<tr>
<td>Xenon-133</td>
<td>5.25</td>
<td>Diagnostic</td>
<td>Lung function</td>
</tr>
<tr>
<td>Strontium-89</td>
<td>50.5</td>
<td>Pain relief</td>
<td>Bone Metastases</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>73.8</td>
<td>Therapeutic</td>
<td>Cancer: cervical/lung/neck/mouth/tongue. To prevent restenosis after balloon angioplasty</td>
</tr>
<tr>
<td>Samarium-153</td>
<td>1.95</td>
<td>Pain relief</td>
<td>Bone Metastases. In development for new therapies.</td>
</tr>
<tr>
<td>Rhenium-186</td>
<td>3.78</td>
<td>Pain relief</td>
<td>Bone Metastases</td>
</tr>
<tr>
<td>Iodine-125</td>
<td>60.1</td>
<td>Therapeutic</td>
<td>Cancer: prostate/eyes</td>
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<tr>
<td>Yttrium-90</td>
<td>2.67</td>
<td>Pain relief</td>
<td>Arthritis</td>
</tr>
<tr>
<td>Erbium-169</td>
<td>9.4</td>
<td>Pain relief</td>
<td>Arthritis</td>
</tr>
<tr>
<td>Lutetium-177</td>
<td>6.71</td>
<td>Therapeutic</td>
<td>Various types of cancer</td>
</tr>
<tr>
<td>Holmium-166</td>
<td>1.12</td>
<td>Therapeutic</td>
<td>In development: liver/blood cancer and other therapies</td>
</tr>
</tbody>
</table>
BNCT is a tumour-targeting form of radiotherapy under development, which currently can only be performed at nuclear research reactors, such as the HFR. BNCT is based on the ability of the isotope ¹⁰B to capture thermal neutrons to produce two highly energetic particles, i.e. a helium (α particle) and lithium ion. When produced selectively in tumour cells, the particles can in principle destroy the cancer cells, whilst sparing the surrounding healthy tissue. BNCT therefore opens up an effective new modality for cancer treatment.

The BNCT facility consists of an irradiation beam (HB11), an irradiation room, a patient and facility monitoring area, whilst outside the reactor containment building, a BNCT Wing is available, which is used to prepare patients for treatment and is directly connected to the facility inside the containment building via the emergency exit.

A suitable beam for BNCT should have:
- a fluence of thermal neutrons resulting from the moderation of epithermal neutrons in tissue, thus allowing patient treatment in a reasonable amount of time (less than one hour), i.e. required neutron fluence > 3 x 10¹²n/cm²,
- an effective mean neutron energy of < 10 keV, thus avoiding as much as possible high doses from proton recoil
- a gamma-ray contamination of the beam, with a gamma dose = 1.0 Gy
- a fast neutron contamination of the beam, with a fast neutron dose = 1.0 Gy, and
- an almost parallel, forward directionality of the beam.

To achieve these characteristics, a specially designed filtered neutron beam has been installed consisting of materials placed inside the beam tube, between the reactor and the patient treatment position. The filter materials and thicknesses to produce the radiation beam characteristics consist of: 15 cm Al; 5 cm S; 1 cm Ti; 0.1 cm Cd; and 150 cm liquid Ar. The therapy position is 5.5 m from the reactor core and the filtered beam is some 3 m in length. The beam is very parallel, i.e. it has a high forward directionality, giving an advantage in the penetration of neutrons into the tissue and less dose to the surface of the patient. Furthermore, the patient can be positioned without restrictions some 30 cm from the beam opening with no virtually loss in beam intensity.

In addition, at beam tube HB7, a pure thermal neutron beam is available to perform high accuracy prompt gamma ray spectroscopy, which is used to determine the amount of boron in blood in patients during treatment, and the amount of boron in cancer cells and healthy tissue provided from uptake studies in humans.

Clinical trials on BNCT at the HFR include:
- Phase I Clinical Trial of BNCT for Glioblastoma using the boron compound BSH (EORTC Protocol 11961)
- Early phase II study on BNCT in metastatic malignant melanoma using the boron carrier BPA (EORTC Protocol 11011)

Studies are also in progress for the extra-corporal treatment of liver metastases, as well studies into the use of BNCT for non-cancerous diseases, such rheumatoid arthritis.
Radiotoxicity and long lifetime of radioactive waste components can be reduced by means of neutron irradiation. Due to its flexible experiment design options, the HFR is very well suited for testing of innovative fuel and targets within the area of transmutation of waste. The radioactive waste components that are most relevant for transmutation are plutonium, americium, iodine and technetium, which have all been tested in the HFR.

Transmutation related research is performed within international frameworks. The European network EFFTRA (Experimental Feasibility of Targets for Transmutation) in which JRC-IE, JRC-ITU, CEA, EdF, FZK and NRG participate, has launched experiments for transmutation of americium, technetium and iodine. Within the European framework programme experiments regarding Pu-burning are presently performed and new experiments on Am transmutation are being prepared. Innovative designs for Pu-burning were performed in cooperation with European and Japanese partners.

In order to study the transmutation of Americium-241 two experiments named EFTTRA-T4bis and EFTTRA-T4ter were performed at the HFR for up to 650 full power irradiation days in the frame of the EFFTRA collaboration.

Experiments with americium and plutonium inert matrix fuel are performed in so-called SHIFT sample holders, in which sealed capsules are clamped into a steel frame within the sample holder. Thermocouples are inserted into a small Nb tube inside the capsule such that central temperatures can be assessed. After loading, the sample holder is filled with sodium in order to have optimal cooling during irradiation. The sample holder is then placed into a TRIO rig, which can accommodate three independent experiments in one in-core HFR position. The TRIO rig can be rotated in order to get homogeneous fluence or it can be placed into other HFR positions for the most appropriate flux level.

Experiments with technetium and iodine are performed in an aluminum sample holder which is placed into an in-core position. For iodine transmutation, experiments are also performed in the pool-side facility, which allows for temperature ramping of the sample. These ramping studies allow to study the behaviour of the gas release as a function of temperature.
The Hot Cell Laboratories (HCL) in Petten are closely connected to the HFR as they provide a means of safe handling of highly radioactive materials. The work done in the HCL can be divided into four main areas:

- Radio-isotopes for the pharmaceutical industry
- Materials testing
- Research on nuclear fuel
- Packaging and conditioning of (highly) radioactive waste

The work is carried out in over 30 hot cells, with a staff of about 60 people. A few characteristics are:

- A monthly load of iridium-192 is handled in five concrete (130 cm) hot cells.
- Several batches of molybdenum-99 are made each week in 10 purpose-built lead shielded hot cells. The liquid waste is handled in a specially designed lead shielded unit.
- Destructive testing of nuclear fuel places special demands on the leak tightness of a hot cell. A cell line of lead shielded cells is used for various microscopic examinations (light, EPMA, SEM, TEM). Non-destructive testing, such as gamma scanning, puncturing and visual examination takes place in the concrete cells.

- Three lines of lead shielded cells are dedicated to materials testing. Test types comprise tensile, flexural, fatigue and creep testing, impact and fracture toughness, (re-) welding, thermal diffusivity, expansion, density.
- One steel cell is connected to the pool of the reactor and is used for handling of specimens and rigs, and dry loading of containers.

Furthermore, HCL provides an Actinides Laboratory, a Tritium Laboratory and a Graphite materials testing line.

Neutron Transmutation Doping of Silicon

Silicon is used as the basic material in the semiconductor industry. The silicon is doped with a small concentration of other atoms (e.g. boron or phosphorous) in order to get the optimum semiconductor characteristics. In most cases these other atoms are inserted into the silicon during the production of the silicon ingots. A very homogeneous doping of phosphorous in the silicon ingot can be induced by irradiation of the ingots in a nuclear reactor, which causes the transformation of $^{30}\text{Si}$ into $^{31}\text{P}$. This neutron transmutation doped silicon has a very homogenous electrical resistance and is therefore very suitable for power electronics.

In the HFR, a silicon doping facility is in operation and to meet growing demand, another facility is under construction. The facility in operation is a facility for ingots with an outer diameter of 101.6 mm (4 inch) and a maximum length of 500 mm. The new facility will be suitable for ingots with outer diameters of 127 and 152.4 mm (5 and 6 inches respectively).
Neutron radiography (NR) is a non-destructive inspection and testing technique. It produces images of components and structures, on film or real time devices using neutrons as the penetrating irradiation. In its nuclear application, it is feasible to image radioactive devices and to penetrate heavy materials such as steel, lead and uranium. In the non-nuclear applications, it provides an important additional non-destructive technique being capable to image materials which are undetectable by X- and gamma-radiography (e.g. hydrogen bearing materials). At the HFR, two NR installations are available.

The underwater NR-camera is mainly used for thermal and epithermal/fast NR examination and inspection of mostly radioactive irradiation devices and test objects, e.g. fuel rods at various stages in their experimental programmes. A special object holder and flanges are available for reproducible positioning and guidance of the components to be investigated. Images (80 x 600 mm) are recorded on nitrocellulose film, dysprosium foil or gold foil and transferred to X-ray film.

Neutron beam tube HB8 can be employed for inspection of non-radioactive materials and structures. For non-nuclear applications, a choice exists between a thermal beam, a filtered thermal and a sub-thermal neutron beam. This capability is attractive for R&D of the related inspection techniques. Images (240 x 300 mm) from this facility are recorded on nitrocellulose film (with radioactive objects), on gadolinium foil/X-ray film or by a low light TV-system.

The NR-laboratory is equipped with specialized equipment to handle all types of X-ray and nitrocellulose film and to evaluate the images by special image evaluation equipment such as a profile projector, a travelling microdensitometer and an image analysis system.
The large variety of irradiation facilities frequently requires complex fabrication techniques, instrumentation and the use of sophisticated assembly processes. On-site specialised teams for design, manufacturing, instrumentation and assembly are available, and a dedicated quality control process is present that ensures high reliability operation of in-pile and out-of-pile equipment. These specialised teams produce approximately 90% of the irradiation devices that are used in the HFR.

Fabrication, instrumentation and assembly

(above) Photo showing the assembly of an irradiation experiment.

(Below) X-ray inspection photo of the high temperature irradiation experiment SICCROWD

(Top picture) Photo showing a detail of the outside of an irradiation device.

(Below) Active gas handling for vented capsule operation, with purge control and monitoring instrumentation cabinet.
The monitoring of neutrons in the irradiation positions and capsules is of paramount importance for the evaluation of experimental results and product yields. Activation foil selection and analyses are tailored for the type and duration of the irradiations. NRG has extensive experience in the optimisation of irradiation monitoring and neutron dosimetry leading to amongst others optimised neutron metrology sets. Depending on the location of the activation foils in the rig design, neutron fluences and spectra are derived through interpolation of measurement results for each individual specimen or location in the capsules. Reference dosimeter monitor-sets have been designed for use in research and power reactor cores. Analysis of the measurements is done using the approach shown below. This approach involves the use of modern database and computer models.

In order to optimise the control and understanding of irradiation experiments, an on-line remote data analysis system has been developed at the HFR. This system is based on the computer programme MATLAB and a database interface. The system can be entered using a secured line over the internet. The output is visualised on-line in a clear manner. This system can be used for all kinds of instrumented HFR experiments. 

Screen dump showing the on-line remote data analysis output. The left side of the figure shows a cross section of the experiment, including the locations of the thermocouples and the pressure lines. The pressure and thermocouple readings are shown at the right side of the figure.