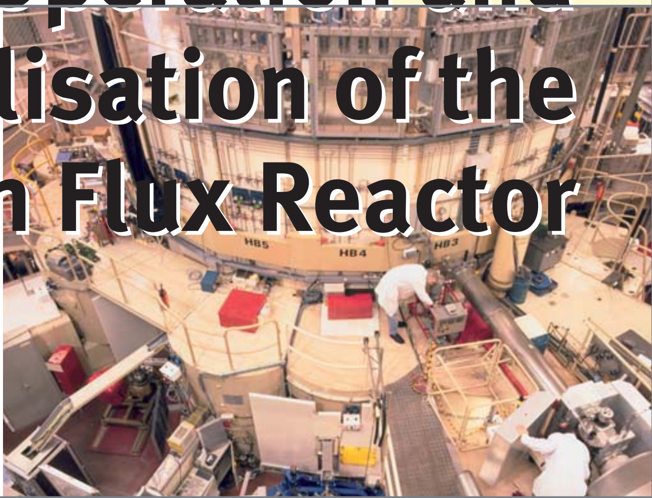
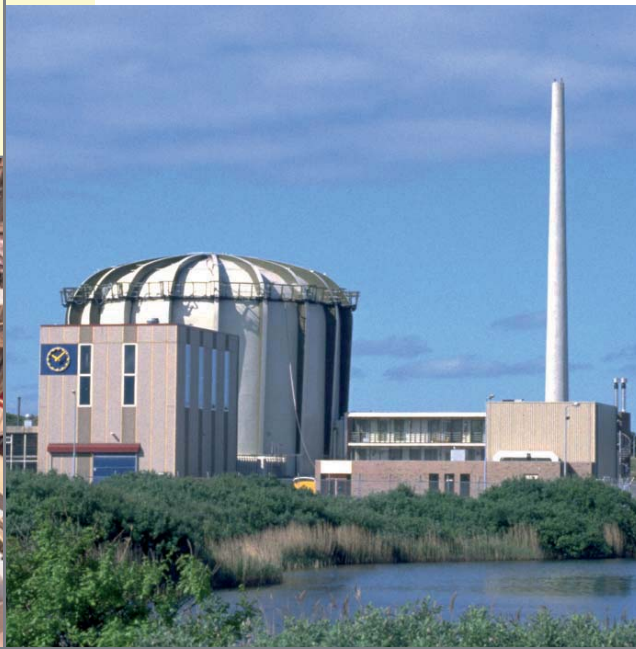
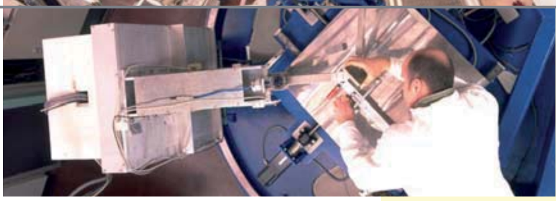
ISSN 1018-5593/1830-5997

Operation and Utilisation of the High Flux Reactor







Annual Report 2008

EUROPEAN COMMISSION

JRC

Institute for Energy

EUR 23952 EN

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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.

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Luxembourg: Office for Official Publications of the European Communities, 2008

European Commission

EUR 23952 EN
ISSN 1018-5593 / 1830-5997
DOI 10.2790/12971
ISBN 978-92-79-12986-5

Printed in the Netherlands, Aranea Grafimedia

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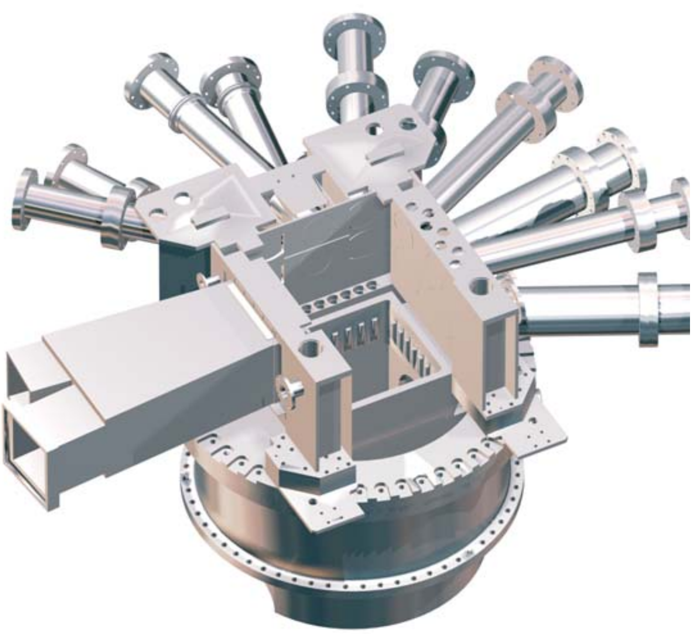
Introduction

The High Flux Reactor (HFR) Petten, managed by the Institute for Energy (IE) of the JRC of the European Commission, is one of the most powerful multi-purpose materials testing reactors in the world. The HFR is of the tank-in-pool type, light water cooled and moderated and operated at 45 MW. In operation since 1961, and following a new vessel replacement in 1984, the HFR has a technical life beyond the year 2015. The reactor provides a variety of irradiation facilities and possibilities in the reactor core, in the reflector region and in the poolside. Horizontal beam tubes are available for research with neutrons and gamma irradiation facilities are also available. Furthermore, excellently equipped hot cell laboratories on the Petten site provide virtually all envisaged post-irradiation examinations possibilities. The close co-operation between JRC and NRG on all aspects of nuclear research and technology is essential to maintain the key position of the HFR amongst research reactors worldwide. This co-operation has led to a unique HFR structure, in which both organisations are involved. JRC is the owner of the plant (for a lease of 99 years) and the plant and budget manager. JRC develops a platform around HFR as a tool for European collaborative programmes. NRG operates and maintains the plant, under contract, for JRC and manages the commercial activities around the reactor. As of February 2005 NRG has become the holder of the operation licence granted under the Dutch Nuclear Energy Law. Furthermore each organisation provides complementary possibilities around the reactor activities, such as the hot cell facilities of NRG or the experiment commissioning laboratory of JRC. HFR is also in the core of the Medical Valley association.



During the last three decades the HFR has been operated from Supplementary Programmes regularly discussed by the European Council.
On 19 February 2004, the European Council adopted a three-year supplementary research programme to be implemented by the Joint Research Centre for the European Atomic Energy Community (2004-2006) concerning the operation of the Community's High Flux Reactor. This supplementary programme has been subsequently extended by one year (2007) and therefore expired on 31 December 2007. The operation of the HFR continued throughout 2008 without a supplementary research programme while efforts were made to base its operation and exploitation on an independent and more durable legal regime. Since these efforts failed, it will now be necessary to provide for continued financial support under a new supplementary research programme.

The High Flux Reactor suffered a protracted malfunction in 2008. A malfunction in the HFR's primary cooling water system was discovered during the reactor's annual maintenance period in August. As a result, the reactor operator NRG decided against restarting the reactor. The decision, motivated by uncertainties on the potential safety relevance of the finding, had a major impact not only on the research activities carried out with the HFR, but also on the worldwide availability of radioisotopes for medical applications of which the HFR is one of the main irradiation facilities.
Following a detailed safety study and the implementation of extra technical measures the reactor was put in condition to safely operate for a restart early in 2009.

Roberto May

HFR: Reactor Management

HFR Operation and related services

At the start of 2008 the planned cycle pattern consisted of a scheduled 284 operation days and two maintenance periods of 24.3 and 27.5 days respectively. During the spring maintenance period the planned modifications as well as the yearly containment leak test were successfully performed. During the summer maintenance period the extended reactor vessel inspection and the inspection of the bottom plug liner, as well as several safety-related modifications were also successfully performed.

In August 2008 NRG performed an extensive In-Service Inspection of the reactor, which included monitoring earlier detected deformations in the primary cooling system. During this inspection an unexpected and unknown phenomenon was observed. Periodically, a very small trace of gas bubbles escaped from the pipe wall into the primary cooling system. Because the safety relevance of this anomaly was unknown at that moment the operator NRG decided not to start up the planned irradiation cycle of September.

Subsequently, extensive investigations have been conducted into the cause of deformations and the gas bubble stream. Experts concluded that the deformations and the gas bubble stream are caused by corrosion on the concrete side of the liner, affecting the aluminium material of the pipe.

Following this, a detailed safety study was performed. On the basis of this study extra technical measures have been introduced, such as the installation of sealing and detection systems; so that safe reactor operation can be assured.

The remaining cycles from 2008-07 to the end of the year were cancelled and the HFR was in operation during 170 days only (Figure 1). This resulted in an actual availability of

Table 1 - 2008 operational characteristics

			OPERATING TIME					SHUT-DOWN TIME				
Cycle Begin-End	HFR Cycle	Generated Energy	Planned	Low Power	Nominal Power	Other Use	Total	Planned	Unscheduled	Number of Interruptions		Stack Release (of Ar-41)
2008		MWd	hrs	h.min	h.min	h.min	h.min	h.min	h.min	PD*	Scram	Bq x E+11
01.01 - 23.01	08.01	999.57	536	00.48	534.54		535.42	16.00	00.18		2	4.1
24.01 - 24.02	08.02	1292.32	688	03.17	687.38		690.55	77.00	00.05		1	5.9
25.02 - 26.03	08.03	1247.92	664	04.27	663.54		688.21	75.20	00.19		2	4.2
27.03 - 17.04	Maintenance period							528.00				
18.04 - 18.05	08.04	1335.85	688	03.17	711.02		714.19	29.41				4.8
19.05 - 22.06	08.05	1382.61	760	05.38	735.11		740.49	80.00	19.11		1	4.9
23.06 - 28.07	08.06	1336.99	707	02.52	710.26		713.18	150.38	00.04		1	5.3
29.07 - 23.08	Maintenance period and ISI							624.00				
24.08 - 21.09	08.07	Cancelled	664						696.00			
20.09 - 21.10	08.08	Cancelled	664						744.00			
22.10 - 21.11	08.09	Cancelled	688						768.00			
22.11 - 23.12	08.10	Cancelled	592						672.00			
24.12 - 31.12	09.01	Cancelled	176						240.00			
	TOTAL :	7595.26	6827	20.19	4043.05		4063.24	1580.39	3139.57		7	29.2
Percentage of total time in 2008 (8784 h) :				0.23	46.03		46.26	17.99	35.75			
Percentage of planned oper. time (6827 h) :				0.30	59.22		59.52					

*PD: Power decrease

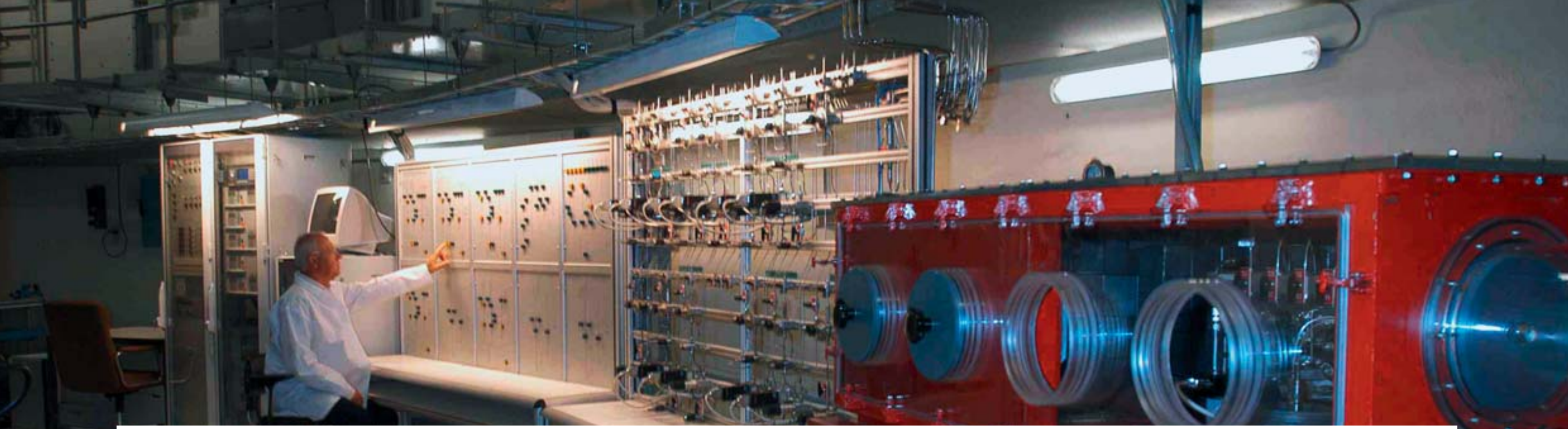


Figure 1 - HFR availability

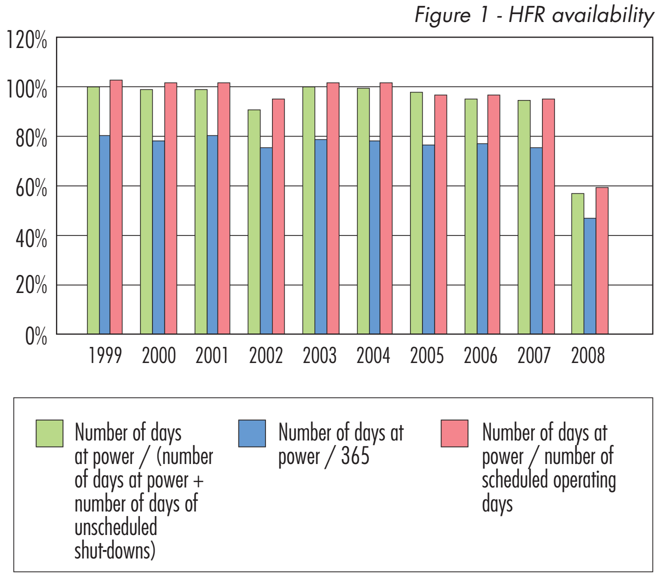
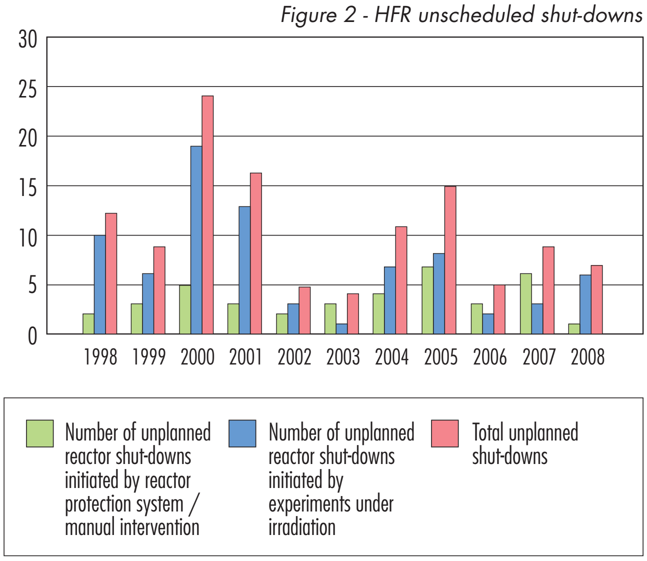


Figure 2 - HFR unscheduled shut-downs



56.41 % with reference to the originally, scheduled operation plan. Nominal power has been 45 MW, with a total energy production of approximately 7,595 MWd, corresponding to a fuel consumption of about 9.5 kg ^{235}U.

At the beginning of the reporting period, the HFR was in operation for the performance of cycle 2008-01. Nearly all the cycles were started earlier than originally scheduled. At the scheduled end of 45 MW operation of each cycle, shutdowns included activities performed in the framework of the regular HFR's operators training.

The detailed operating characteristics for 2008 are given in Table 1. All details on power interruptions and power disturbances, which occurred in 2008, are given in Table 2. It shows that seven scrams occurred (see also Figure 2). Two of these scrams were due to human intervention, i.e. human error, while one scram was caused by loss of off-site power and the remaining four scrams were due to intervention by the safety systems of the experimental devices.

In 2008 many people visited the reactor. Apart from the usual visits of international colleagues and relations in the medical world, the cycle based "HFR Open Days", attracted many visitors. A total of 886 people divided over 177 tours were guided through the facility during the first half of 2008.

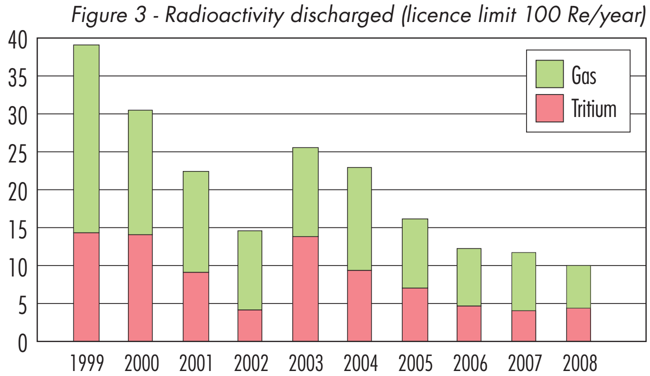
Maintenance activities

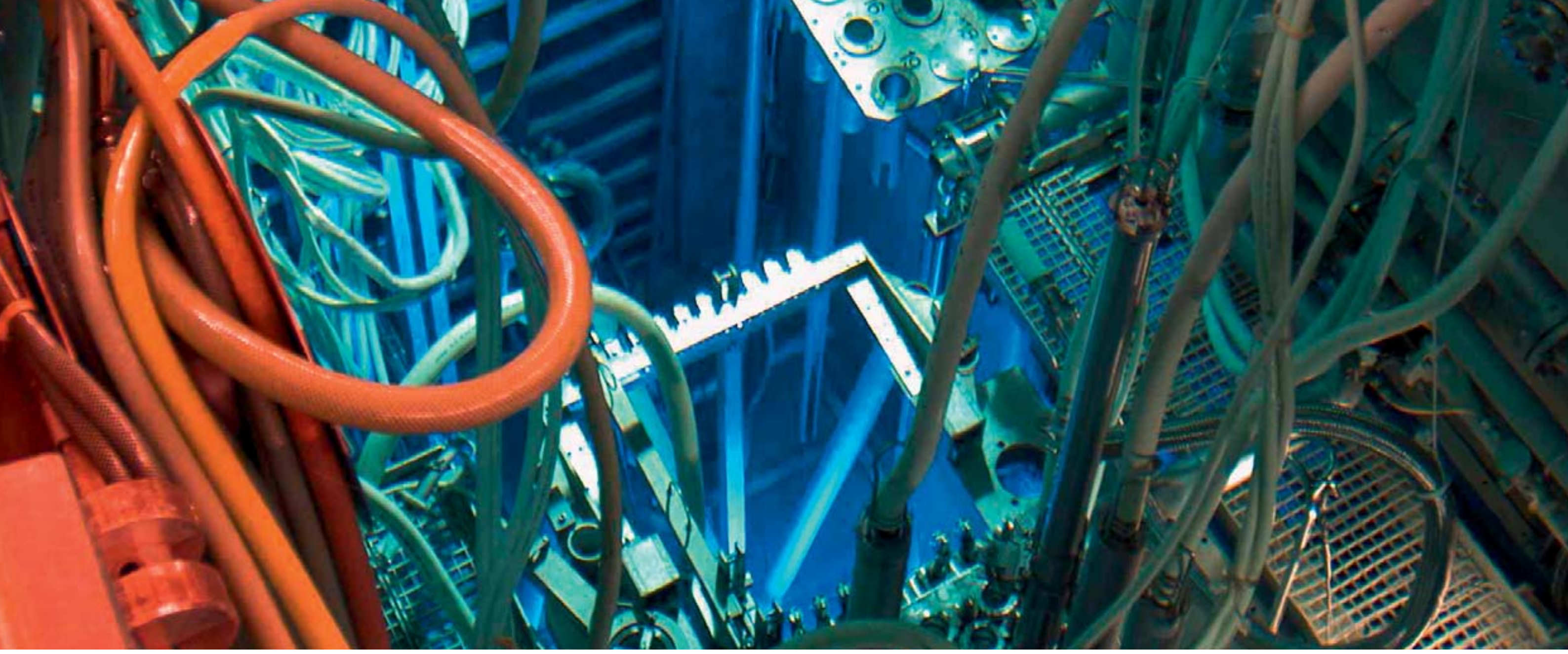
In 2008 the maintenance activities consisted of the preventive, corrective and break down maintenance of all Systems, Structures and Components (SSC's) of the HFR as described in the annual and long term maintenance plans. These activities are executed with the objective to enable the safe and reliable operation of the HFR and to prevent inadvertent scrams caused by insufficient maintenance. The periodic leak testing, as one of the licence requirements (0.2 bar overpressure over a 24 hours duration) and the extended In-Service Inspection including the measurements of the bottom plug liner, were all successfully performed. As part of the HFR Modification Plan several modifications were performed, including:

- Measures to prevent the safety related consequences of postulated flooding of parts of the HFR buildings;
- Measures to mitigate the effects of postulated fires in buildings and compartments relevant to safety;
- Renewal of the cables and cabinets for the experimental devices;
- Renewal of ageing (non-fire retardant) cables;
- Design of an alternative shut-down system;
- Implementation of a reactor scram in case of low water level in the reactor pool;
- Improvements on the Uninterrupted Power Supply (UPS) and the Emergency Power Supply;
- Design and construction of a Remote Monitoring System;
- Improvements on the HFR interlock.

All modifications were implemented after the revision of the plant description and operating instructions and following successful commissioning and testing.

Figure 3 - Radioactivity discharged (licence limit 100 Re/year)





DATE	CYCLE	TIME OF ACTION	RESTART OR POWER IN-CREASE	NOMINAL/ ORIGINAL POWER	ELAPSED TIME TO		DISTURBANCE CODE				REACTOR SYSTEM OR EXPERIMENT CODE	COMMENTS
					RESTART OR POWER INCREASE	NOMINAL/ ORIGINAL POWER	1	MW	2	3		
2007		hour	hour	hour	h.min	h.min						
03 Jan	08.01	00:35	00:45	00:55	00.10	00.20	AS	0	A	E	Mains power supply	Loss of off-site main power supply causing a reactor scram.
23 Jan	08.01	06:14	06:22	07:00	00..08	00.46	AS	0	P	M	Exp. 354-01	The mechanical locking device of experiment Tycomo-01 did not function correctly causing a scram on coolwater system 41 and 42.
17 Feb	08.02	05:51	05:56	06:09	00.05	00.18	AS	0	P	H	Exp. 266-07	During execution of the check-out of experiment Prometeo -05 (266-05), a pressure drop in the cooling water system occurred resulting in a low pressure alarm on Prometeo -07 causing a reactor scram.
27 Feb	08.03	18:06	18:19	19:24	00.13	01.18	AS	0	E	I	Exp. 361-01	During locating of experiment "INCOMODO" (347-01) in its irradiation position the temperatures of TC4 and TC 6 of experiment "CONFIRM" (361-01) suddenly increased causing a reactor scram.
14 Mar	08.03	16:44	16:50	17:16	00.06	00.32	AS	0	P	I	Exp. 267-09	During flow adjusting of cooling water system 39 of production facility 267-09 the high pressure limit was exceeded, causing a reactor scram.
12 Jun	08.05	17:07	17:12	19:30	00.05	02.23	AS	0	E	I	Exp.361-01	Spontaneous temperature rise on all thermocouples of experiment CONFIRM (361-01) with a scram as result. Despite thorough investigation on a possible cause no other deviations could be found.
26 Jul	08.06	12:32	12:36	12:54	00.04	00.22	AS	0	E	H	Exp. 368-01	Accidentally the cooling water safety switch KS-02 of experiment BODEX (368-01) which was locked at "out-position" of the PSF was operated, with a scram as result.

1. LEADING TO
- automatic shut-down AS
- manual shut-down MS
- automatic power decrease AP
- manual power decrease MP

2. RELATED TO
- reactor R
- experiment E
- auxiliary system A
- production facility P

3. CAUSE
- scheduled S
- requirements R
- instrumentation I
- mechanical M
- electrical E
- human H

Table 2 - 2008 full power interruptions of HFR

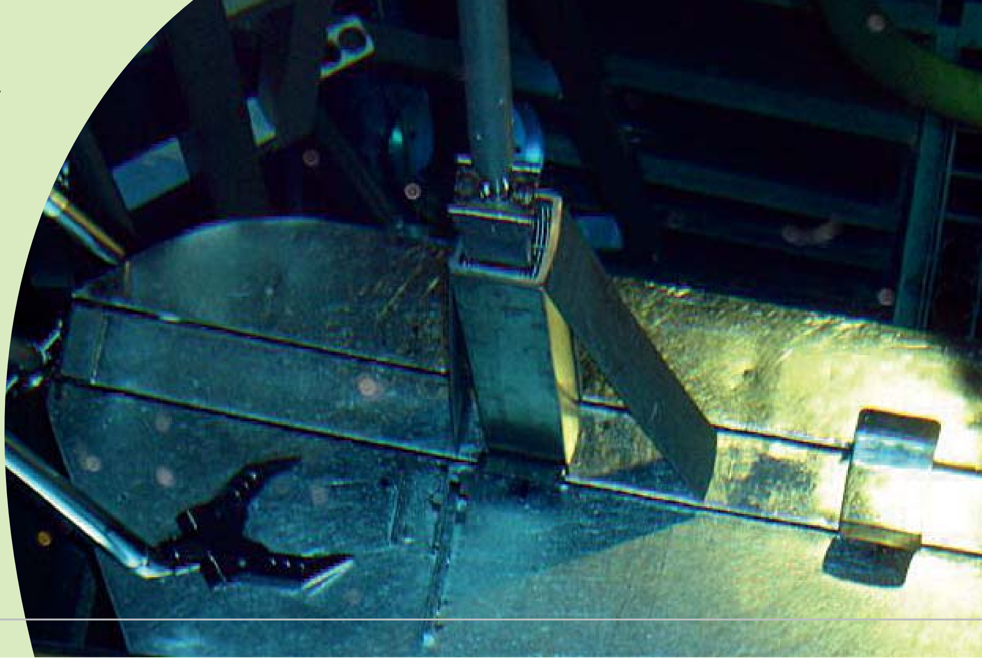


Figure 4 - The AleqLA-01 is one of the US owned test elements

Fuel Cycle

Front end

During 2008, new Low Enriched Uranium (LEU) fuel elements and control rods were inspected at the manufacturer's site and delivered on schedule. Since May 2006, the HFR is running completely on LEU fuel.

Figure 5 - Handling of the US owned test elements in the HFR pool

Back end

In 2008, two shipments of High Enriched Uranium (HEU) spent fuel took place in MTR2 containers to the Dutch Central Organisation for Radioactive Waste (COVRA). In total 64 elements, of which 56 fuel and eight control rods, which are occupying two positions in the HABOG building for High Level Radioactive waste at COVRA. At the end of 2008, 28 positions out of the 48 positions (including the six reserve positions) are still available in the HABOG. The last 84 HEU elements stored in the HFR pool are planned to be shipped in 2009 over three shipments.

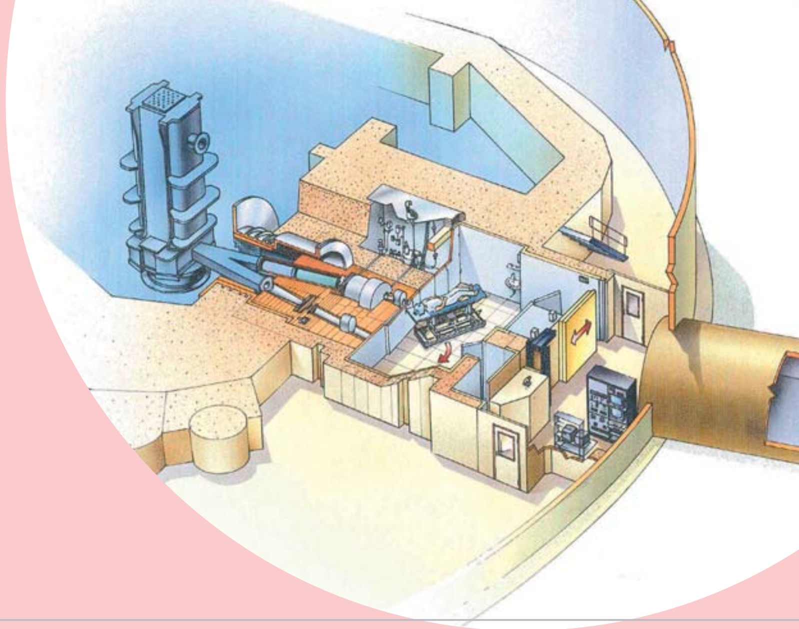
The Gesellschaft für Nuklear-Service (GNS) carried out the compulsory 6-years inspection of one of the MTR2 containers (including the sea container, holding the MTR2 container during transport). Furthermore, the prolongation certificate of the licence for all worldwide existing Castor MTR2's was issued by the German authorities and validated by the Dutch Ministry of Housing, Spatial Planning and the Environment.

In August 2008, a road transport, containing eight LEU test assemblies, was carried out between Petten and Bremerhaven (DE). This fuel originates from irradiation campaigns of specimens of United States property, which therefore needed to be shipped back to the USA.

Figure 6 - Preparations for the road transport to Germany with the 8 US owned LEU test assemblies

Figure 7 - The sea container, holding the MTR2 container during transports, is unloaded

Figure 8 - The basket holding HEU elements is ready to be loaded into a canister in the hot cell at COVRA



The unique BNCT Facility at The HFR Petten

Medical Applications

BORON NEUTRON CAPTURE THERAPY - BNCT

The year 2008 was a monumental year for this IE Action on the Development and Exploitation of Neutron Capture Therapy. After almost two decades of pathfinding medical research, which included performing clinical trials on cancer patients at the High Flux Reactor, hosting many successful Ph.D. studies from students from around the world and with over 200 publications, the decision was taken to close the Action. Despite this, throughout the year the Action continued to make significant contributions to the development of BNCT in Europe and further afield.

The BNCT project in Petten was the first in Europe where BNCT was carried out on cancer patients. The clinical trials are still the only trials worldwide that were carried out in a truly multinational (pan-European) way. The specific role of IE/JRC, in close cooperation with NRG Petten, included treatment planning, technical coordination, upkeep of the facility and quality assurance. The success of the endeavour stimulated other groups in countries in Europe such as Sweden, Finland, the Czech Republic and Italy to set-up and start clinical trials on BNCT. One of the goals of the BNCT work in Petten was always to encourage and stimulate the development of BNCT throughout Europe and indeed further afield too.

Clinical trials on BNCT at the IE

Since the end of 2007, it has not been possible to obtain a new licence to re-start clinical trials. Of the three clinical trials carried out in previous years, trial EORTC Protocol 11001 on "^{10}B-uptake in different tumours using the boron compounds BSH and BPA" continued during 2008, with the measurement of more tissue and blood samples that had been taken from cancer patients in the operating theatre at the University Hospital in Essen and sent to Petten for measurements by prompt gamma ray spectroscopy at beam tube HB7.

Application of BNCT to other types of cancer – Liver metastases

In collaboration with the University Hospital Essen, investigations continued to look into the possibility of irradiating explanted, cancerous livers at the HFR. In previous years, a special facility was built in Petten to hold the liver during treatment. Following tests on the facility in previous years, it was possible in 2008 to test the whole procedure on an explanted liver, which had been taken from a pig in the operating theatre at the Central Animal Facility of the Medical Faculty in Essen.

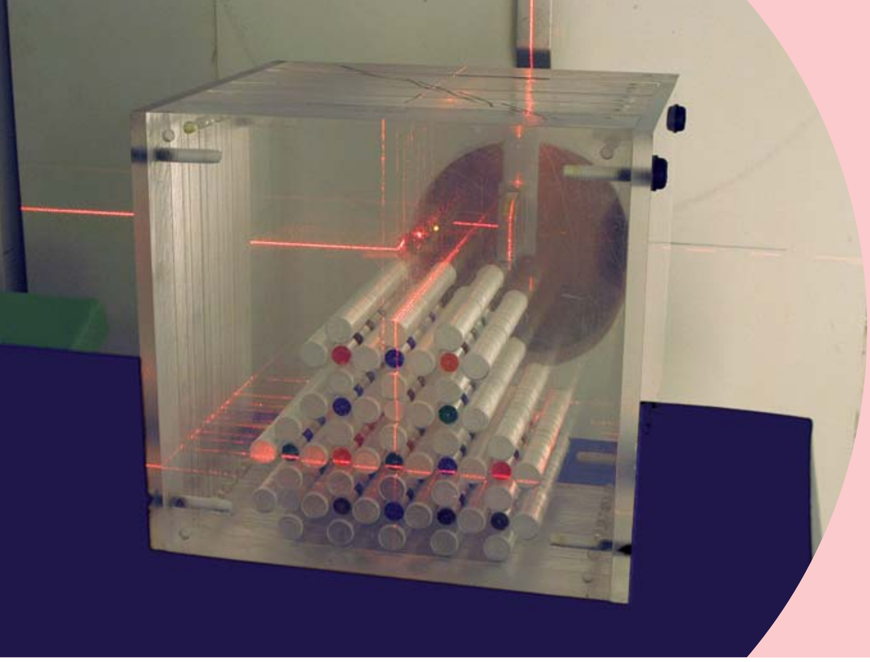
BNCT is based on the ability of the isotope ^{10}B to capture thermal neutrons to produce two highly energetic particles, i.e. a helium (α particle) and lithium ion, which have path lengths in tissue roughly equal to the diameter of a single cell. Hence, when produced selectively in tumour cells, the particles can destroy the cancer cells, whilst sparing the surrounding healthy tissue. BNCT therefore offers to the clinician the opportunity to limit the damage to the tumour only, which is indicative of its inherent advantages over current advanced radiotherapy techniques applied in conventional radio-oncology units. For the IE, the critical component in BNCT is the availability of a strong, reliable neutron source, i.e. the HFR.

Arrival of the liver from Essen

Preparations to irridiate the liver

Placing the liver into the LIF

Following irradiation



JRC Institutional Programme on BNCT
The research and development activities are supported in the JRC's Institutional Research programme. Studies include treatment planning, improvement of the BNCT facility, dosimetry and testing of new boron-containing compounds by means of cell culture irradiations.

Facility
At the beginning of the year, the western half of the BNCT Wing was re-newed and is now completely watertight from the perils of the wet and prevailing westerlies.

Dosimetry
To strengthen the expertise and the independence of the group from external partners, a new gamma detector system was purchased and installed to enable the group to perform their own activation measurements on irradiated materials, in particular activation foils. Furthermore, as part of the final stage in the Ph.D. work, numerous measurement campaigns were performed at HB11 and HB7, using a variety of ionisation chambers, principally types TE(TE), Mg(Ar) and Al(Ar).

Radiobiological Dosimetry
This exploratory research project, which gained funding in 2007 and is supervised by Sander Nievaart, continued into 2008 and was extended to include a collaboration with Stockholm University. As part of this study, IE purchased equipment to assist in the incubation of cells following irradiation.

Conferences and Workshops

International Workshop on "Accelerator based neutron sources for Medical, Industrial and Scientific Applications", Torino, Italy
A workshop was organised by Comitato Eurosea Med to advance the use of accelerators in many applications, but mainly in medicine. One of the criticisms of BNCT is that it is restricted to reactor-based facilities. However, to be able to develop a hospital-based neutron source using accelerators would greatly profit both BNCT and accelerator manufacturers. Within this capacity, the Action Leader (Ray Moss) was invited to give the BNCT perspective on this development, but in particular to give recommendations about the characteristics of any required neutron source.

13th International Congress on Neutron Capture Therapy, Florence, Italy
The Congress is held once every two years and is the principal BNCT Congress. The Petten group is always represented strongly at this Congress due to Petten's status in the BNCT Community. It is the ideal congress to find out about the status of BNCT worldwide and to renew and strengthen close collaborative research programmes.
There were 291 participants from 23 countries. The Petten group gave five presentations, chaired three sessions and co-authored another six papers. Significant progress in the BNCT treatment of recurrent Glioblastoma and Head and Neck cancers were reported from Japan and Finland respectively. Promising progress was also reported on the BNCT treatment of liver, lung, melanoma and other types of brain tumours. Many research programmes at nuclear research institutes in Germany, Italy, UK, Finland, Romania, Bulgaria, USA, Japan, S.Korea, Taiwan, Argentina and Russia were reported. The future of BNCT looks promising for some types of cancers, but there is still, far too few facilities available worldwide. Therefore, the closure of the BNCT activities at Petten only acerbates this situation.
At the Congress dinner, both Neta Roca and Yuan-Hao Liu (Ph.D. students in Petten) were presented with two of the five Ralph Fairchild Awards, which are presented to the best Young Researchers in BNCT over the last two years.
There was an expression of concern by most delegates when it was announced that the future of BNCT research at Petten would more than likely be stopped, unless a fully-funded programme could be found.

International Workshop on "Positron Emission Tomography (PET) for BNCT", Pisa, Italy
This satellite workshop to the above Congress was organised jointly by the IE, University Hospital Essen, CNR Institute of Clinical Physiology and the University of Pisa. The workshop was funded by the JRC's Enlargement and Integration Action. Some 40 participants were present and a full programme was held with experts from throughout the world. A CD of all presentations is available.

Publications
As in previous years, the BNCT group produced a large number of publications, both as principal authors or co-authors. In 2008, six papers appeared in peer-reviewed international journals, seven papers were accepted in 2008 for publication in 2009 and 15 papers appeared in conference proceedings

MEDICAL RADIOISOTOPE PRODUCTION

2008 was a year of two parts. In the first part of the year production was extremely busy; new record levels of irradiations of critical isotopes for medical diagnosis, therapy and pain relief were achieved. Lutetium production moved into the new Jaap Goedkoop Laboratory and an increased range of customers was supplied. Irradiations for industrial applications continued to be strong; while irradiation of silicon ingots to produce Neutron Transmutation Doped (NTD) silicon for use in high voltage and other specialist electronic applications such as Wind Turbine power conversion and Hybrid Car technology also grew well. Production was running at high efficiency levels and with good continuity of supply.

Interesting new product development ideas continued to be acquired, with a number of new projects being established for both conventional application areas, as well as ground breaking areas of medical technology. Existing development projects moved forward well with good progress reported from some clinical trial work.

Unfortunately, in the second half of the year production abruptly stopped with the unscheduled stop of the HFR in August. The lack of production from the HFR threw enormous pressure onto the remaining major reactors in the world that also produce isotopes and significant supply shortages were experienced in every business area. This was particularly acute in the medical area where the short half-life products such as molybdenum (Mo-99), which needs to be produced on a near continuous basis. Worldwide Mo-99/Tc-99m is responsible for between 30-40 million patient scans per year. Shortages of Mo-99 in Europe peaked at levels of 80% in some weeks.

NRG worked closely with the radiopharmaceutical companies, the medical community, governmental departments and the other reactors in the isotope supply network. This was aimed at minimizing supply problems where possible and good co-operation allowed some alternative production routes to be opened and allowed some essential programmes to be maintained. This experience fully underlined the critical role performed by the HFR and the supporting infrastructure within NRG in ensuring the worldwide continuous and smooth supply of isotopes for essential medical services. All the staff associated with isotope production look forward to resuming their role in providing this essential service to society.

Fission Reactor Technology

HIGH TEMPERATURE REACTOR FUEL IRRADIATIONS

Background

The High Temperature Reactor (HTR) is a gas-cooled graphite moderated nuclear reactor concept. The high temperature coolant output, effective fuel use, large R&D experience and robust safety concept make it a very attractive heat and power generating system. The HTR is specifically intended for deployment in an industrial environment.
HTR fuel consists of TRISO-particles, which are uranium oxide kernels coated by a porous graphite buffer layer and a pyrocarbon-siliconcarbide-pyrocarbon coating. 10,000-15,000 of these particles (1 mm diameter) are contained in a graphite matrix in the form of a 6 cm diameter fuel sphere ("pebble") or in the form of finger-thick cylinders ("compacts").
Two irradiation tests of low-enriched uranium fuel types in the HFR were carried out or further prepared to determine their limits with respect to radioactive fission product release with increasing burn-up (enhanced fuel use) and at increased fuel temperature (enhanced efficiency).

The following main activities were carried out during 2008:

HFR-EU1: This irradiation test with an approx. 1200°C central fuel temperature aims at high burn-ups, if possible exceeding those of previous experiments. It started in September 2006 and was continued through the first two reactor cycles in 2008. Significant thermocouple failure in one of the two capsules led to loss of approved minimum safety instrumentation, which was the reason why the experiment had to be put on hold at an achieved burn-up of approx. 11% FIMA. In order to resume irradiation, a new safety case had to be built and approved by the reactor safety committee. Due to the extended HFR outage, the experiment could not be restarted in 2008.

Instrumentation: Experience with various high temperature experiments in the HFR has triggered a new effort on instrumentation, in particular gamma spectrometry for fission gas analysis from experimental fuel irradiations and high temperature thermocouples. Gamma spectrometry is used to monitor off-gas from HTR fuel irradiation experiments for possible fission gas release. Previously, gas samples were collected in the reactor and then manually carried for analysis to a different building on-site. To reduce the workload and increase the measurement frequency, gamma spectrometry equipment was installed and commissioned. It will be put into service as early as the HFR-EU1 irradiation will be resumed. Thermocouples in irradiation tests are usually considered safety relevant instrumentation, which implies that a minimum number of them must remain operational with sufficient precision until the end of irradiation. However, it is known that high temperature and neutron irradiation not only cause a strong signal drift of thermocouples, but can lead to complete failure by various mechanisms. Mechanical and corrosion issues (impure helium) equally contribute to thermocouple failure. Several approaches were identified to render thermocouples resistant to this particular environment: larger size, different sheath material, sleeves, coatings etc. Several long-term out-of-pile tests were launched to test the corrosion behaviour of various sheath materials. Manufacturers were contacted to confirm the feasibility of thermocouples with these sheath materials.

Figure 9 - Gamma spectrometer in HFR

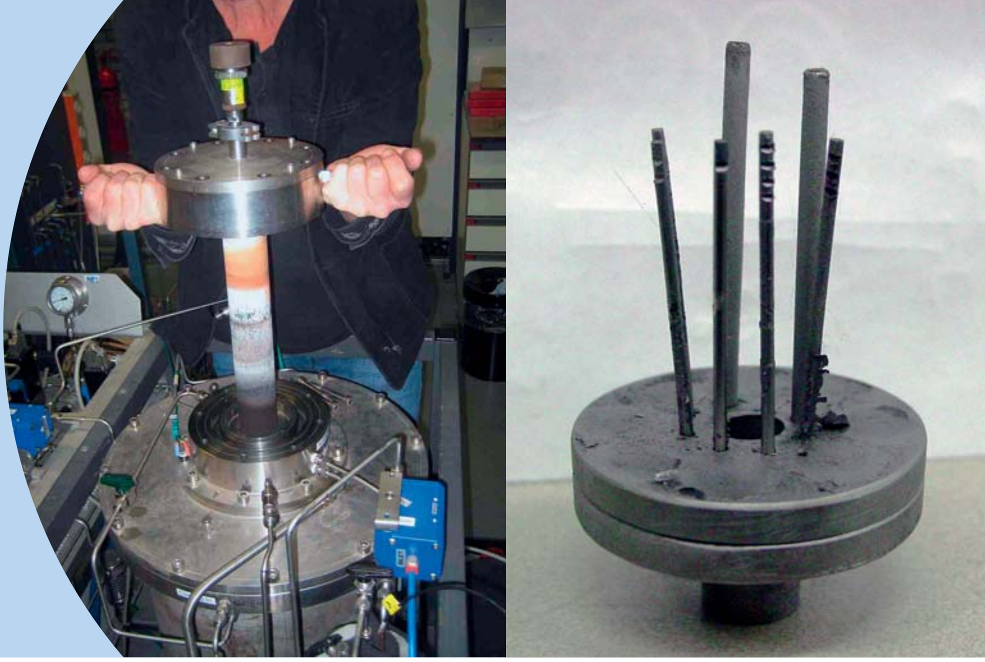


Figure 10 - Test furnace for carburization test of various materials

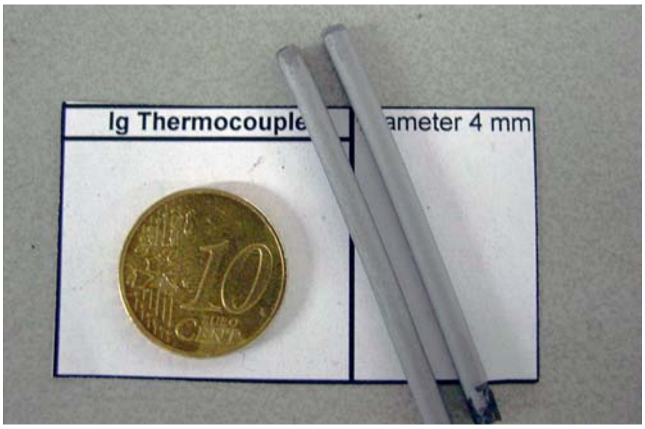
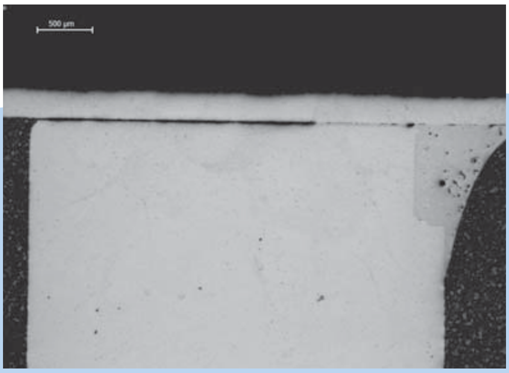
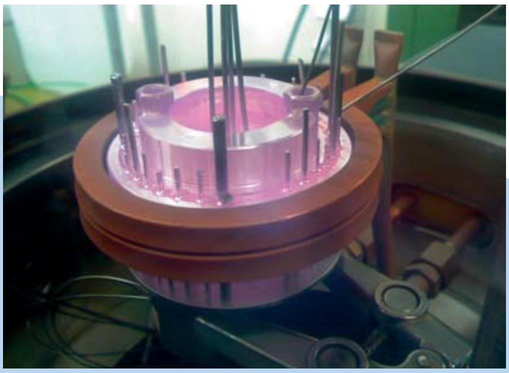


Figure 11 - Ig-type thermocouples tested (thermocoax)

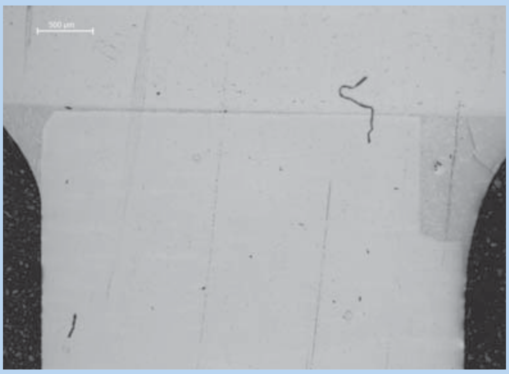
HFR-PBMRF1: Preparation of this irradiation for the South African PBMR prototype project continued in the frame of a bilateral cooperation agreement. Due to delays in the licensing process of the fuel fabrication facility, fuel delivery had to be postponed to 2009. Start-up of the experiment is foreseen by early 2010. To exclude premature termination of this planned irradiation test, particular emphasis was put on selecting robust thermocouples and placing them strategically inside the irradiation capsule. It is intended to include thermocouples with novel sheath materials in this irradiation test, which requires confirmation of the manufacturing ability, in particular of the leak tight transition and seal between thermocouples and top cap of the capsule. This is usually performed by high temperature brazing. This brazing process was qualified for several different kinds of thermocouple sizes and sheath materials.



Brazing Ig-type thermocouples, diameter 2 mm



Brazing test in an induction furnace



Brazing test on If-type thermocouples sheath

Mo Nb thermocouples brazed

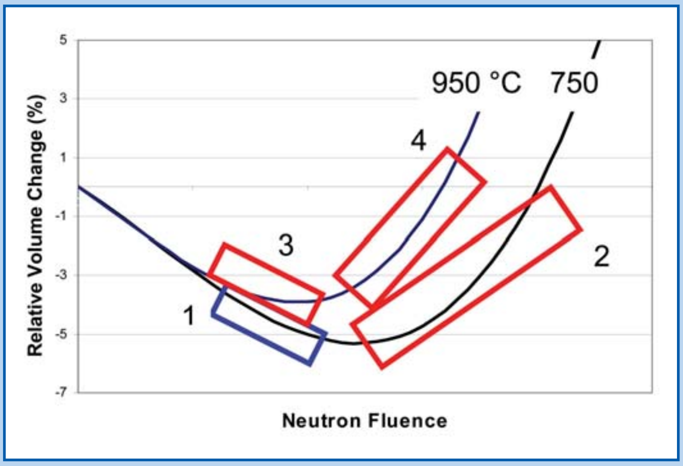


Figure 12 - Schematic overview of the different irradiation experiments

HTR CORE STRUCTURES GRAPHITES

Graphite is a suitable material to be used as a neutron moderator and reflector in nuclear reactors. Due to its excellent high temperature performance graphite is used as a structural material in the HTR design (High Temperature Reactor). The European Commission is supporting research projects (RAPHAEL-IP) for the development of HTR technology with the aim to create the technological requirements for designing and constructing an HTR in Europe. To achieve this new nuclear graphite grades need to be developed and qualified, because the previously used grades are not available anymore.

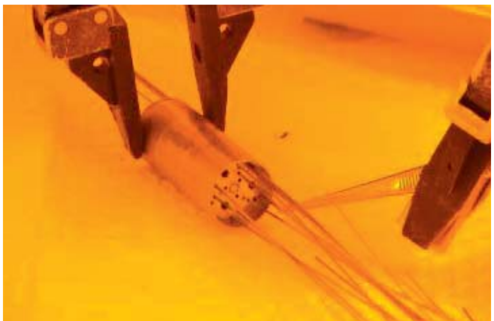
The properties of graphite are changing significantly and non-linearly under neutron irradiation. Therefore the graphite properties need to be obtained at different neutron dose levels. NRG plays a leading role in this research of graphite irradiation behaviour for HTR technology. The property curves at two irradiation temperatures, 750°C and 950°C, are produced in four irradiation experiments (Figure 12). A crucial part of the programme is the possibility to reload irradiated (and therefore radioactive) graphite samples in new experiments to be able to measure the properties at different dose levels. To do this it is necessary to build the experiments in a shielded environment, i.e. a hot-cell.

In 2008, the final experiment of the current programme was built in the hot-cells of NRG. It is the high dose experiment irradiated at 950°C to a target dose of 8 dpa. The experiment is loaded with samples that were irradiated up to 7 dpa in the previous experiment (Figure 13). The cumulative dose of these high-dose samples is therefore targeted at 15 dpa.

The 950°C experiment started irradiation in HFR in July 2008. The high-dose experiment at 750°C is still loaded in the HFR, after starting in August 2007. The irradiations of both experiments will finish in 2010.


Loading samples


Sealing drums


Sliding drums over thermocouples

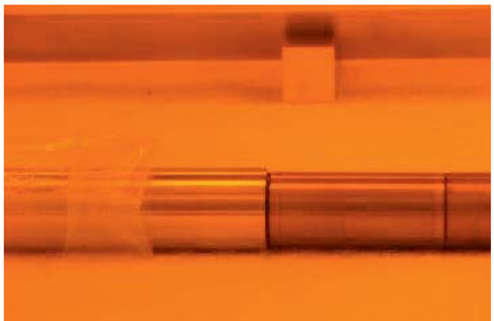

Positioning containment tube

Figure 13 - Building experiments in a hot-cell

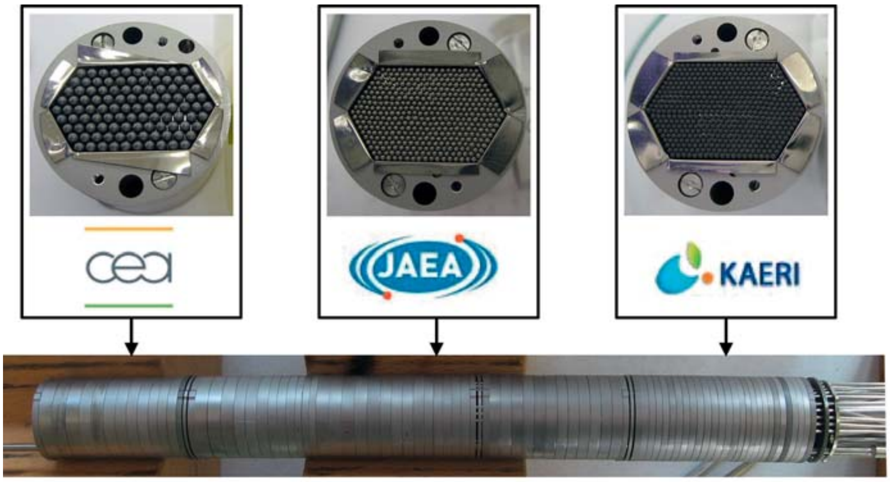


Figure 14 - Overview of the PYCASSO-I irradiation and assembly

(V)HTR FUEL PERFORMANCE CODE QUALIFICATION TESTS

Within the Raphael (V)HTR 6th Framework EU-programme, the PYCASSO experiments have been devised to investigate coating behaviour under irradiation. Samples have been included from CEA (France), JAEA (Japan) and KAERI (Republic of Korea), which makes this irradiation a real Generation IV effort.

The experiment is a separate effect test, where the influence of fuel (coating corrosion or micro structural change due to fission products), thermal gradients, and variation in coating microstructure and dimensions have been minimized by the use of dummy kernels (Al_2O_3 and ZrO_2), high conductivity particle holder material combined with low energy production of the kernels, and strict (fabrication) quality control and selection procedures respectively.

The purpose of the experiment is threefold for the partners involved:

- for CEA to determine the behaviour of pyrocarbon under irradiation, especially the interaction of pyrocarbon swelling and creep with SiC coating layers. The results will be used to validate and improve HTR fuel performance modelling;
- for JAEA to investigate the behaviour of ZrC coatings, which have been successfully manufactured, but require post-irradiation investigation and characterization;
- for KAERI to determine the influence of fabrication of pyrocarbon layers with different densities on the behaviour under irradiation.

The PYCASSO-I irradiation is a completely new design, accommodates temperature regions of 900, 1000 and 1100°C, and contains 76 separate particle sample holders. An overview is shown in Figure 14. The irradiation started in the third cycle of 2008, and temperatures have been successfully achieved, and maintained. This is due to the large experience in experimental design and quality control, as illustrated in Figure 15. A second similar irradiation (PYCASSO-II) is expected to be introduced in the HFR core in 2009.

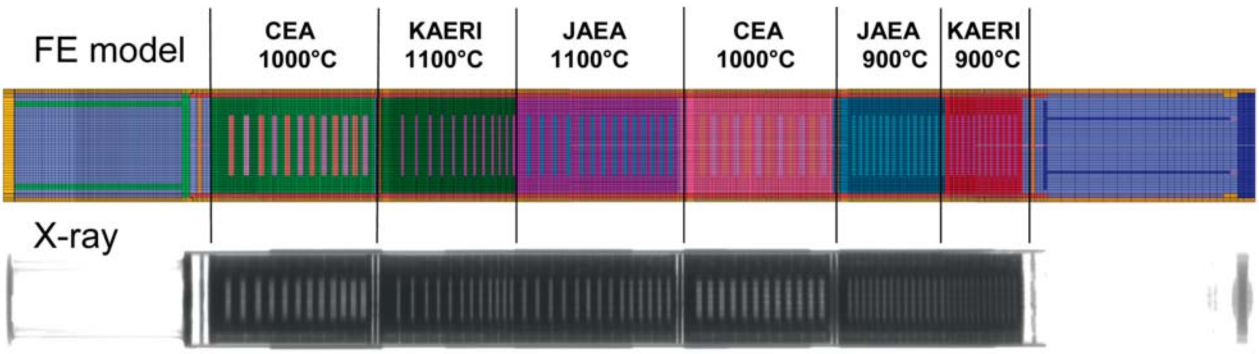
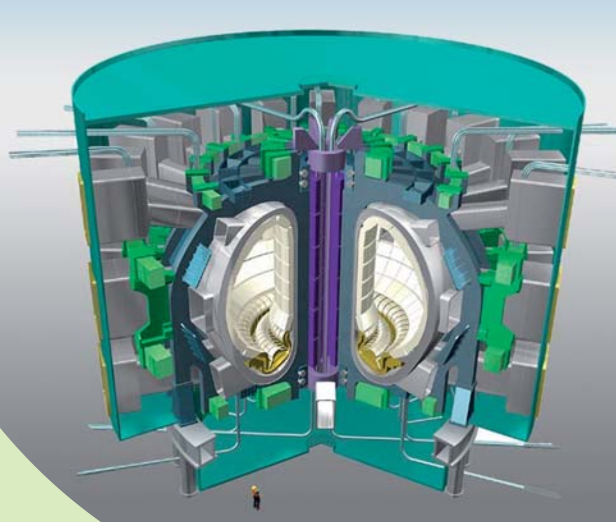


Figure 15 - Comparison between the Finite Element Design model, and the X-ray of the assembled experiment, showing that the assembled experiment is in excellent agreement with the thermo-mechanical design model.



Fusion Reactor Technology

HFR's high versatility provides 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 the hot cell laboratories to perform post-irradiation testing. The main areas of interest are the ITER vacuum vessel, the development of high heat flux components and blanket structures, and the development of the reduced activation materials: 9-Cr steels and innovative materials such as fibre reinforced composites. In addition, irradiation behaviour of ITER diagnostic instrumentation and the in-vessel parts of heating systems require dedicated assessments and testing programmes. As part of the qualification of materials supporting the licensing of a future reactor, the design of the International Fusion Materials Irradiation Facility (IFMIF) is under development. The HFR provides ample opportunity to qualify specific materials for the IFMIF target section, instrumentation and mock-ups. Presentations of the activities on ITER, DEMO and the roles of HFR were delivered to the top Fusion Symposia and Conferences.

ITER Vessel/In-vessel

In one of the European design concepts, the ITER first wall panels are attached to the blanket modules by bolts. NRG investigates the behaviour under neutron irradiation of PH13-8Mo as candidate material. The irradiation campaign aims to measure the response of this material in terms of yield stress hardening, elastic fatigue resistance and fatigue crack propagation up to 2 dpa. After the irradiation of the specimens in a modified SUMO-type experiment, with two temperature zones at 200 and 300°C the dismantling took place. In 2008 the major part of the post-irradiation examinations took place. The final report is expected in 2009.
NRG assisted the ITER Central Team in updating the ITER Materials properties Handbook (MPH). The assessment and verification of the irradiation effects on low cycle fatigue properties of RAFM steel was finished.
A new test facility for ITER primary wall modules is under construction, which will allow close simulation of thermal fatigue and simultaneous neutron loading in the HFR pool side. The conceptual design of this experiment (POSITIFE) was finished and manufacturing will start early 2009. NRG also developed with TNO alternative manufacturing routes for thick tungsten claddings on copper-base substrates. Explosive forming of thick stainless steel sections was demonstrated by Exploform BV, in a joint effort with NRG and TNO to provide alternative manufacturing solutions for the ITER vacuum vessel. The experimental part of both projects on the cladding and the vessel were finished in 2008.

Sub-modules for the Helium Cooled Pebble Bed Concept

The four Pebble Bed Assembly (PBA) experiments were irradiated in the HFR from 2003 to 2004. The experiment has been developed as a sub scale segment of a test blanket as will be tested in ITER. The neutron spectrum in the HFR resulted in an ITER relevant nuclear heating and temperature profile inside the pebble beds, which gave representative thermo-mechanical loads. For the evaluation of the interaction of materials due to neutron irradiation, thermo-mechanical stresses and chemical interaction in a Test Blanket Module were concluded.
Due to the stresses in the pebble beds probably in combination with presence of tritium and gas production, beryllium pebbles showed a large porosity in the pebble-pebble and pebble-Eurofer contact areas. The lithium titanate pebbles stayed intact, but showed discolorisation near the Eurofer, sintering and an increase in porosity. The lithium silicate pebbles showed severe cracking along the grain boundaries. In 2009 a new Scanning Electron Microscope will be installed in the Hot Cell Facility and some of the preparations will be examined for chemical interaction.

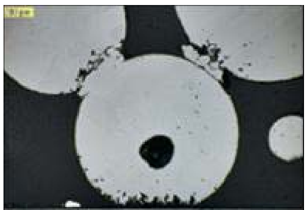
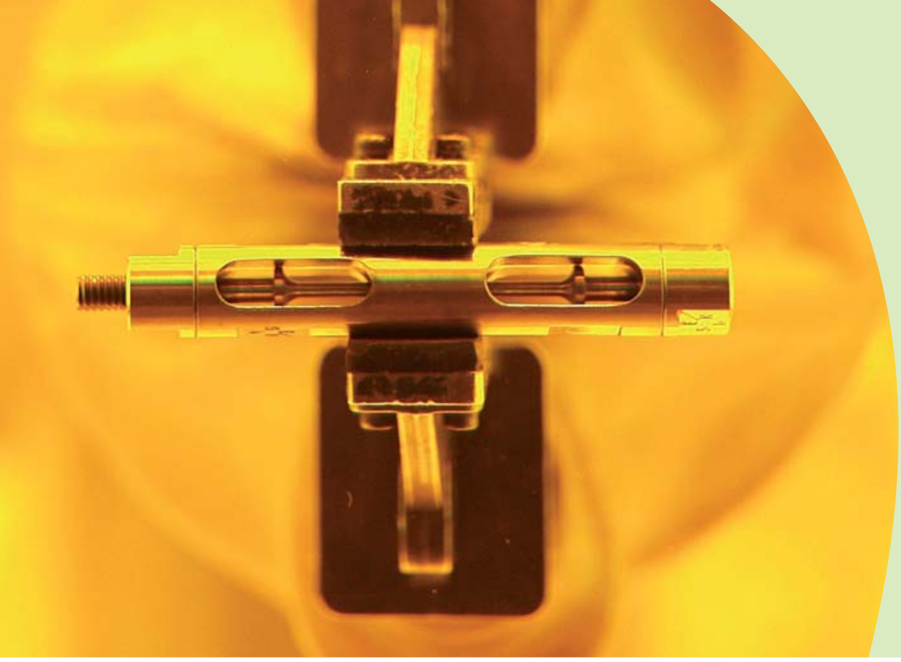


Figure 16 - Beryllium pebble-pebble and pebble-Eurofer interaction, observed in all PBA

Figure 17 - Lithium orthosilicate from PBA #4

Figure 18 - Lithiummetatitanate from PBA #3



Functional Fusion Blanket Materials

In 2008 the dismantling and post irradiation testing of EXOTIC 9/1 has been completed. The in-pile tritium release experiments in the meta-titanate pebble bed have been analyzed and evaluated with the out-of-pile tritium release from the Temperature Programmed Desorption measurement. A part of the pebbles were examined with optical microscopy. Findings suggest that the large, closed porosity in the pebbles could explain the very slow tritium release during irradiation in response to the fast temperature transients.
The HICU experiment (High-fluence Irradiation of breeder Ceramics) started successfully in early 2008, with the aim at long-term (up to two years) irradiation of ceramic pebbles. HICU is a cadmium shielded experiment in order to tailor the HFR neutron spectrum towards a fast/thermal ratio, which is more favourable for the desired dpa/burn-up ratio. After two years in a high flux position (C–row), this dpa/burnup ratio will lead to changes in the ceramic crystal structure and therefore is expected to deliver key properties for definition and selection of grades to be used in the ITER TBM programme.

The objective of the HIDOBE (High Dose Beryllium irradiation) project is to quantify the long-term behaviour in terms of swelling, creep and tritium retention for fusion application and validate models for the thermo-mechanical behaviour of beryllium under irradiation conditions and tritium kinetics in beryllium. Beryllium pebble stacks are irradiated in the HFR for 2 and 4-year periods. In the framework of the IEA agreement on Radiation Damage Effects in Fusion Materials, partners in the EU, Japan and the Russian Federation provided different grades of beryllium specimens. The first of these two high dose irradiations of beryllium specimens, HIDOBE-01 was finished in 2008 and the dismantling started after achieving its target dose of 3,000 appm helium. The experiment contained a few piggy-backs of ceramic breeder pebbles, complementary to the shielded HICU case. HIDOBE-02 will continue in 2009 and 2010 to accumulate a total dose of 6000 appm helium production in beryllium.

In the area of lithium, lead-based blanket concepts, in-pile operation of the LIBRETTO-4/1and 4/2 rigs continued, following a longer outage resulting from the failure during unloading of a neighbouring experiment. The experiments are aimed at the permeation characteristics of Eurofer tubes under relevant irradiation parameters, in nominal 350°C and 550°C regions. The Tritium Measurement Station (TMS) is used to monitor and control the experiment. Both first and second containments are swept with a He + 1000 ppm H_2 gas flow for tritium extraction. This allows direct comparison of tritium production and permeation.

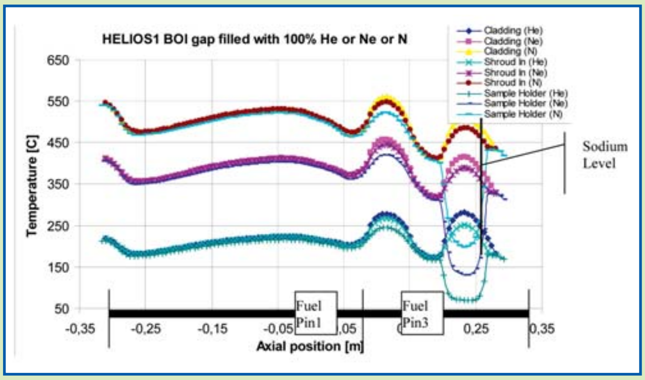


Figure 20 - Axial temperature profile of HELIOS1 at BOI, when the gas gap between the sample holder and the QUATTRO channel is filled with 100% Helium, Neon or Nitrogen

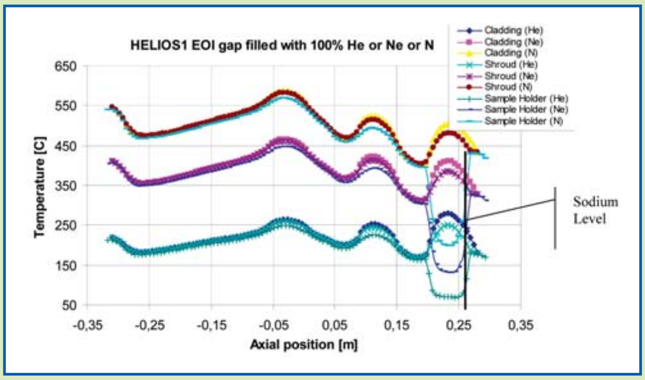


Figure 21 - Axial temperature profile of HELIOS1 at EOI, when the gas gap between the sample holder and the QUATTRO channel is filled with 100% Helium, Neon or Nitrogen

Partitioning and Transmutation Technologies

HELIOS

Objective

Americium is one of the radioactive elements that contribute to a large part of the radiotoxicity of spent fuels. Transmutation by irradiation in nuclear reactors of long-lived nuclides like ^{241}Am is therefore, an option for the reduction of the mass and radiotoxicity of nuclear waste. The Helios experiment, as part of the FP6 EUROTRANS Integrated Project on Partitioning and Transmutation, will deal with irradiation of U-free fuels containing americium. The main objective of the HELIOS irradiation is to study in-pile behaviour of U-free fuel targets such as CerCer (Pu, Am, Zr)O_2 and $Am_2Zr_2O_7$+MgO or CerMet (Pu, Am)O_2 +Mo, in order to gain knowledge on the role of microstructure and temperature on gas release and fuel swelling. During the irradiation of such fuels, a significant amount of helium is produced due to the nuclear transmutation of americium. The study of the gas release is of vital importance to allow better performance of the U-free fuels. Two different approaches are followed to reach early helium release:

1. Provide release paths by creating open porosity, i.e. release paths to the plenum gas. Therefore, in the HELIOS test matrix a composite target with a MgO matrix containing a network of open porosity has been included.
2. Increase target temperature in order to promote the release of helium from the matrix. Americium or americium/plutonium zirconia based solid solutions along with CerMet targets have been included in the test matrix to study the effects of the temperature. The role of the plutonium in association with americium is to increase the temperature of the target at the beginning of irradiation.

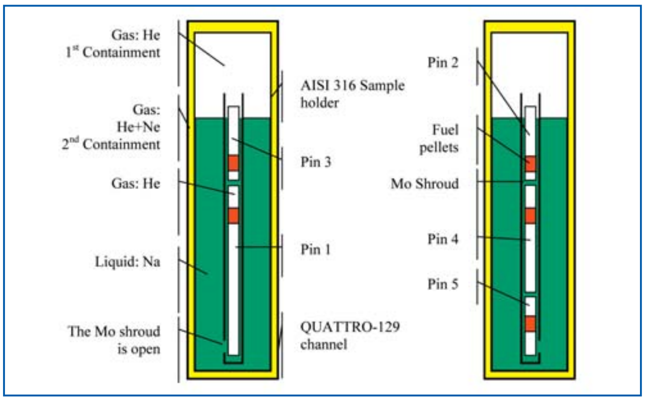
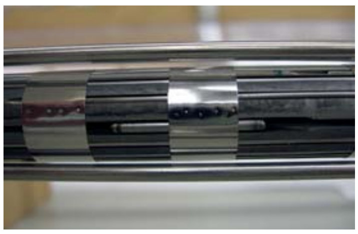


Figure 19 - Schematic view of the irradiation experiment. HELIOS1 on the left (pins 1 and 3), HELIOS2 on the right (pins 2, 4, and 5)

Achievements 2008

The experiment was planned to be conducted in the HFR in the first quarter of 2007. Due to the innovative aspects of the fuel, the fabrication had some delays, as well as the final safety analyses of the original design showing some unexpected deviations. In addition, the HFR reactor has been unavailable since August 2008. Due to the reasons described here, the experiment has been postponed. HELIOS should start in the first quarter of 2009 and will last 280 full power days. Nevertheless, some relevant milestones have been reached during 2008. The experiment has been redesigned and all the calculations (nuclear and thermo-mechanical) have been repeated (see Figure 20 to Figure 23). It has been split into two parts (HELIOS1 and HELIOS2) which will be irradiated together (see Figure 19). Moreover, due to the high temperature achieved in the cladding and to the high amount of helium produced during transmutation the experiment previously designed for a high flux position has been moved to a lower flux position. The assembly of the whole experiment has been completed.

The Helios irradiation during assembly



Magnified view of the Helios experiment during assembly

Zoomed view of the Helios experiment during assembly

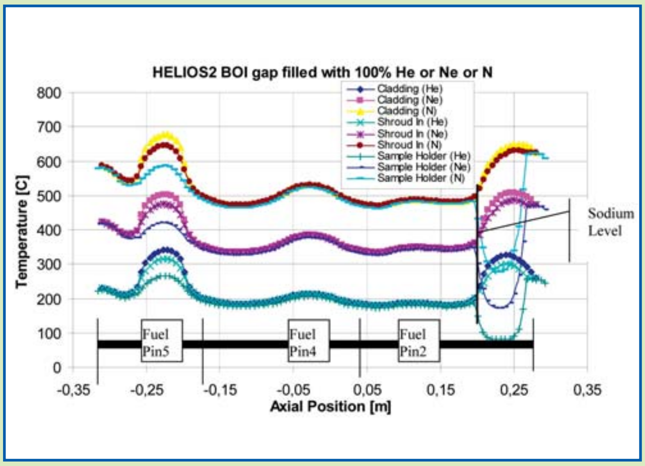


Figure 22 - Axial temperature profile of HELIOS2 at BOI, when the gas gap between the sample holder and the QUATTRO channel is filled with 100% Helium, Neon or Nitrogen

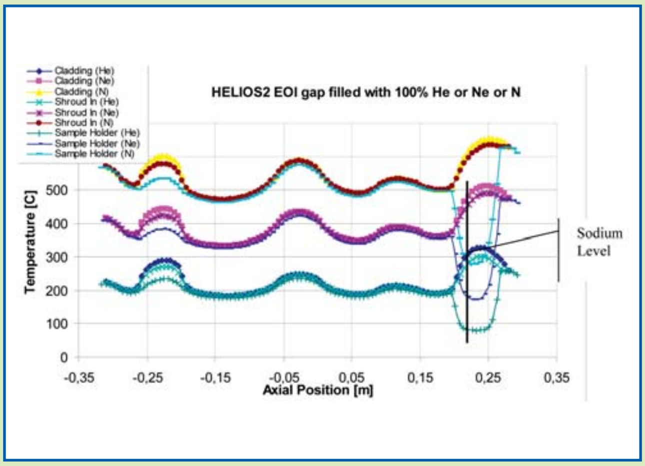


Figure 23 - Axial temperature profile of HELIOS2 at EOI, when the gas gap between the sample holder and the QUATTRO channel is filled with 100% Helium, Neon or Nitrogen

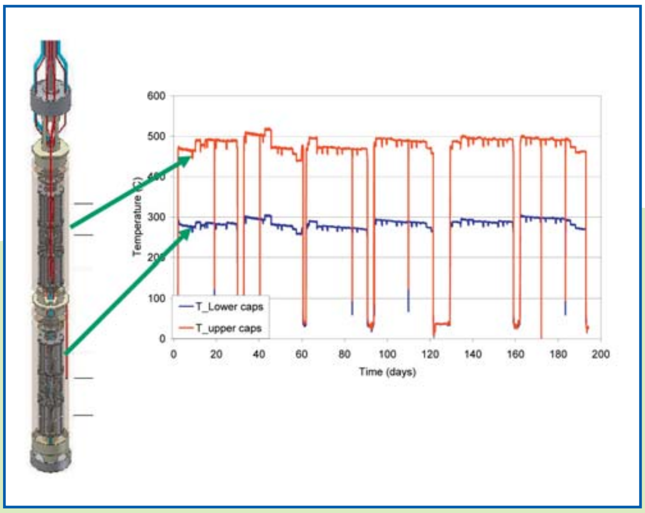
MARIOS and SPHERE

Objectives

Two new irradiations have been discussed and approved during 2008. Both irradiation experiments (namely MARIOS and SPHERE) belong to the FP7 FAIRFUELS project, which has been accepted in 2008.
The main objective of the MARIOS is to test the performance of high Minor Actinides content targets by irradiation in the HFR. This task is of major importance for multi-recycling of Transuranic Elements in future GenIV reactors. The aim of MARIOS irradiation test is also to investigate more closely the behaviour and accommodation of high helium producing MA targets in a uranium oxide matrix carrier. The MARIOS irradiation should start in 2010 and will last for approximately 300 full power days.
In order to assess the expected improved irradiation performance of Sphere-Pac fuels compared to conventional pellet fuel, a dedicated SPHERE irradiation experiment will be performed. For this purpose, Am containing fuel will be fabricated at JRC-ITU and irradiated at HFR. This is the first of its kind, irradiation test, as MA bearing Sphere-Pac fuel has never been irradiated before. The SPHERE irradiation should start in 2011 and will last for approximately 300 full power days.

Achievements 2008

The FP7 FAIRFUELS competitive project has been accepted. The project will start in 2009.



ADS MATERIAL DEVELOPMENT

Objectives

In Europe, an experimental Accelerator Driven System (ADS) for the transmutation of actinides is under development. Liquid Lead Bismuth Eutectic (LBE) will be used as reactor coolant. Lead Bismuth has a low melting point (135°C), but has corrosive properties with structural materials and welds. In addition, transmutation of Bi to the highly radiotoxic ^{210}Po is a safety issue in the design of the ADS. Materials R&D is needed to test the corrosion behaviour of T91, 316L and weld specimens during irradiation in contact with LBE and to examine the deposition of ^{210}Po in the irradiation containers and on the specimens after irradiation. Therefore the irradiation experiment IBIS has been built. This consists of one containment tube with two containers filled with Lead Bismuth Eutectic and Stain less steel/ T91 specimens. The specimens are in contact with the LBE to test the influence of neutron irradiation corrosion behaviour and the influence of the LBE on mechanical properties. A 3-D view of the experiment is shown in Figure 24.

Achievements 2008

The irradiations of the IBIS experiments continued during all irradiation cycles in 2008 and were operated at the target temperatures of 300 and 500°C. For the study of the influence of neutrons on the wetting characteristics of LBE, the third capsule was subject to the same thermal cycling as for the lower temperature capsule in the HFR.
During 2008 the facility for the retrieval of the specimen was designed and built by ECN. Also a dedicated tensile machine was bought to test the specimens in the Fuel Cell line in the HCL. This location is selected because of the presence of the alpha emitting radionuclide ^{210}Po. Together with the HCL management a start has been made with risk inventory and evaluation of the Post Irradiation Test campaign.

Figure 24 - Design of IBIS experiment together with the temperature history of the capsules during irradiation in 2008

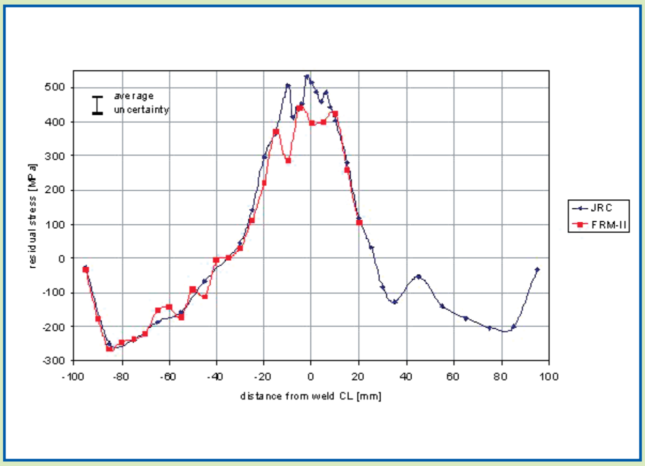


Figure 26 - NET TG2 Auxiliary specimen: welding longitudinal stresses measured at the HFR and at FRM-II, Germany

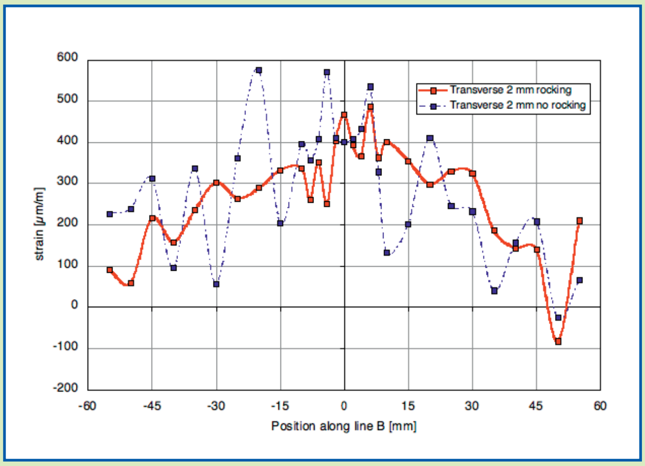


Figure 27 - Impact of measurement procedure in neutron diffraction; specimen "rocking" reduced the scatter in a data set obtained from a coarse grained welded steel plate

NEUTRON BEAM RESEARCH

In 2008 the HFR has been out of operation for almost half a year, a time during which no measurements and no facility testing with neutrons could take place. Nevertheless, for residual stress measurements the first comprehensive experimental campaign was successfully completed at the new diffractometer at beam tube HB5. Figure 25 shows the specimen, which was a ferritic steel plate with a three-bead-slot weld in its centre (NET TG2, see Figure 26), at the new facility. After these first measurements the neutron detector of this facility has been sent for service to the manufacturer, which has rendered the instrument idle for an additional three months. The instrument on HB4 has been operational for the entire period available and several interesting experiments have been made to improve the quality of measurements in materials with large grain size. Figure 27 shows an example of how the scatter in a data set measured on a coarse grained material could be reduced through rotating the sample through a small angular range ("rocking") during the measurements.
NRG has continued to perform structural analyses by powder diffraction using the diffractometer at beam tube HB3a on behalf of Leiden University. Amongst others, materials for applications in batteries have been investigated. At the same time NRG has started the process to bring back into operation the diffractometer at beam tube HB9, which is equipped with a copper double monochromator. Equipment from the previous HB4 and HB5 diffractometers is being reused at this facility.

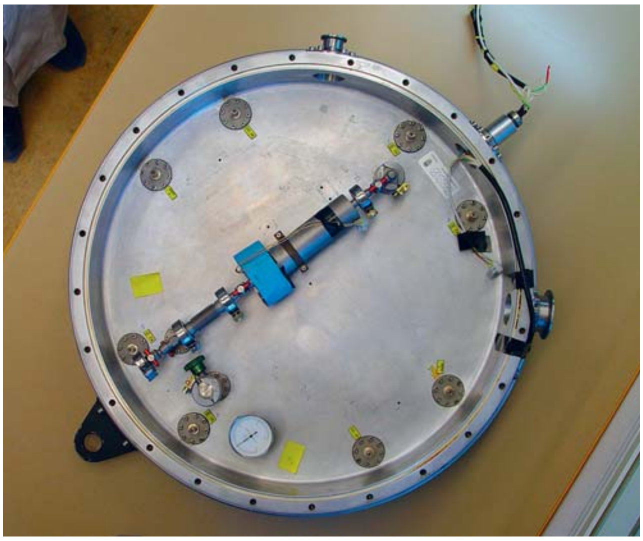


Figure 28 - SANS area detector during repair in JRC laboratory

HFR Small Angle Neutron Scattering Facility Development

The Small-Angle Neutron Scattering (SANS) facility at the HFR has not been used extensively in 2008, as the JRC embarked on the repair of the position sensitive neutron detector during the first half of the year. As no external provider could be identified for this service, the scientific staff undertook to perform this work by themselves (Figure 28). The work was completed; however, this did not happen in time to be able to test the detector with neutrons before the extended reactor shut-down. However, background measurements with the overhauled detector showed its improved performance.
A small facility was developed for the analysis of the neutron wavelength spectrum in the incoming beam of the SANS facility. This machine, which is based on a single neutron beam chopper, works on the time-of-flight principle. It has been possible to measure the spectrum of the SANS beam with some limitations in resolution with this simple device.

Figure 25 - Welded ferritic steel plate from NET TG2 during investigations at new residual stress diffractometer at beam tube HB5

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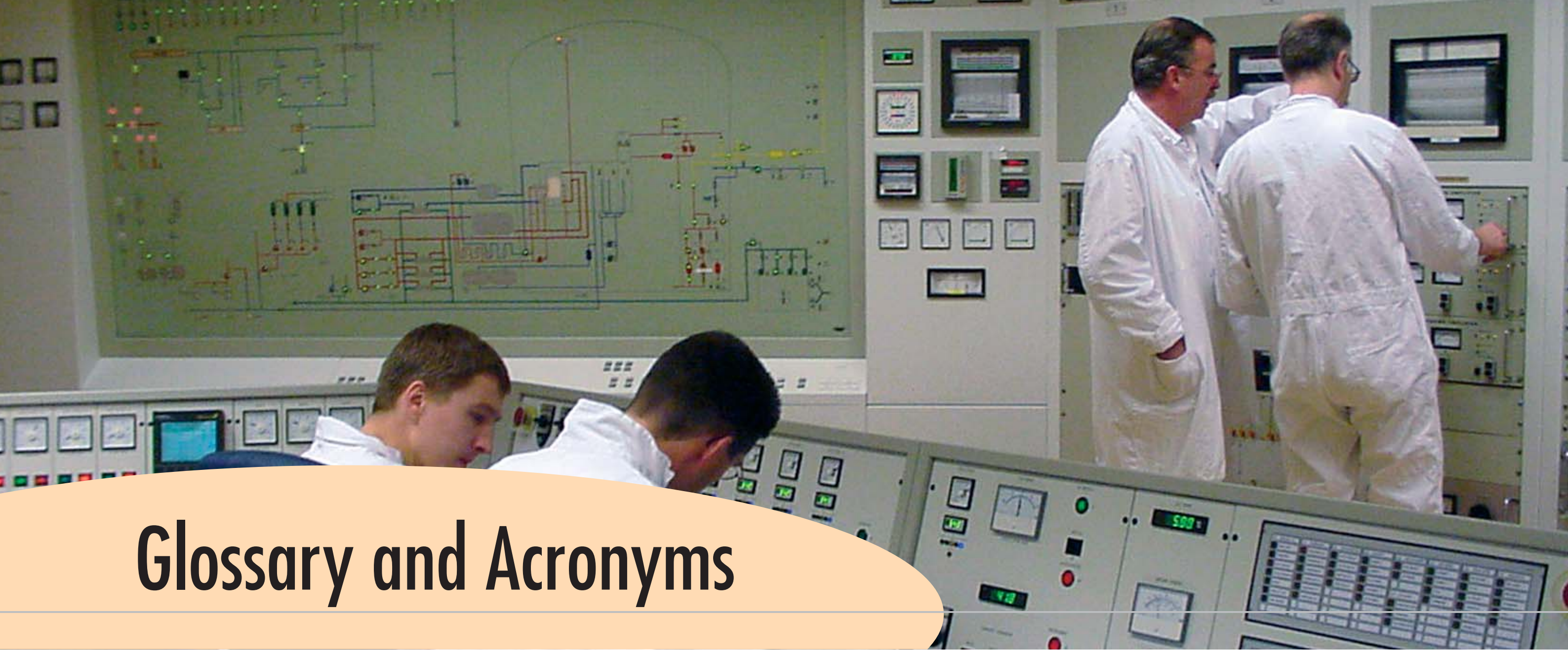

Glossary and Acronyms

ADS	Accelerator Driven Systems
AMES	Ageing Materials Evaluation Studies
BNCT	Boron Neutron Capture Therapy
BPA	Borono-phenylalanine (Boron compound for BNCT)
BSH	Borocaptate sodium (Boron compound for BNCT)
CEA	Commissariat à l'Energie Atomique
CONFIRM	Collaboration On Nitride Fuel IRradiation and Modelling
COVRA	Centrale Organisatie Voor Radioactief Afval
DEMO	Demonstration Fusion Reactor
DG	Directorate General
dpa	displacements per atom
EC	European Commission
ECN	Energieonderzoek Centrum Nederland
EORTC	European Organisation for Research and Treatment of Cancer
EU	European Union
EUROTRANS	European Transmutation
EXOTIC	EXtraction Of Tritium In Ceramics
FAIRFUELS	Fabrication, Irradiation and Reprocessing of FUELS and target for transmutation
FP or FWP	Framework programme
GIF	Generation IV International Forum
HABOG	Interim storage centre for high level waste
HAW	High Active Waste
HB	Horizontal Beam Tube
HCL	Hot Cell Laboratories
HELIOS	Helium in Oxide Structure
HEU	High Enriched Uranium
HFR	High Flux Reactor
HICU	High-fluence Irradiation of breeder Ceramics
HIDOBE	High Dose Beryllium Irradiation Rig
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IE	JRC Institute for Energy, Petten (NL)
IEA	International Energy Agency
INPRO	International Project on innovative nuclear reactors and fuel cycles
ISI	In-Service Inspection
ISNCT	International Society of Neutron Capture Therapy
ITER	International Thermonuclear Experimental Reactor
JAEA	Japan Atomic Energy Agent
JRC	Joint Research Centre
KAERI	Korea Atomic Energy Research Institute
LBE	Lead Bismuth Eutectic
LEU	Low Enriched Uranium
LIBRETTO	LIquid BReeder Experiment with Tritium Transport Option
NCT	Neutron Capture Therapy
NET	Network on Neutron Techniques Standardisation for Structural Integrity
NRG	Nuclear Research and consultancy Group
PBA	Pebble Bed Assemblies
PBL	Peripheral Blood Lymphocytes
PBMR	Pebble Bed Modular Reactor
PYCASSO	PYcarbon irradiation Creep And Swelling/Shrinking of Objects
PSF	Pool Side Facility
R&D	Research and Development
RAFM	Reduced Activation Ferritic Martensitic (steel)
RAPHAEL	ReActor for Process heat Hydrogen And ELectricity generation
RTD	Research and Technological Development
SAFETY-INNO	Safety of Innovative Reactor Designs
SANS	Small Angle Neutron Scattering
SUMO	In-Sodium Steel Mixed Specimens Irradiation
TBM	Test Blanket Modules
TG	Task Group
TN	Technology Network
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (*Netherlands Organization for Applied Scientific Research*)
TYCOMO	TYCO Molybdenum

European Commission

EUR 23952 EN - DG JRC - Institute for Energy
Operation and Utilisation of the High Flux Reactor
Annual Report 2008
Edited by: R. Moss, G. Gouwens - van Rijn, R. May
Luxembourg: Office for Official Publications of the European Communities
2009 - 20 pp. - 21 x 29.7 cm
Scientific and Technical Research Series

ISSN 1018-5593 / 1830-5997
DOI 10.2790/12971
ISBN 978-92-79-12986-5

Abstract

The High Flux Reactor (HFR) at Petten is managed by the Institute for Energy (IE) of the EC - DG JRC and operated by NRG who are also licence holder and responsible for commercial activities.

The HFR operates at 45 MW and is of the tank-in-pool type, light water cooled and moderated. It is one of the most powerful multi-purpose materials testing reactors in the world and one of the world leaders in target irradiation for the production of medical radioisotopes.

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LD-NA-23952-EN-C

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EUROPEAN COMMISSION

ISBN 978-92-79-12986-5

9 789279 129865

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