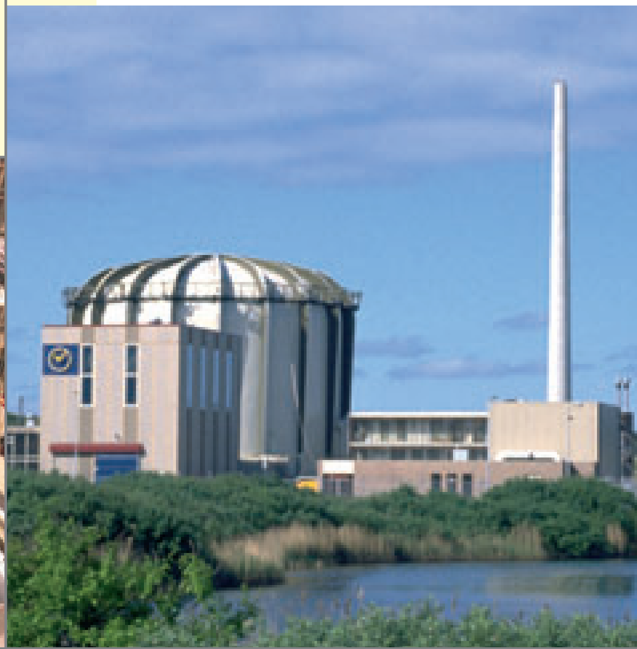
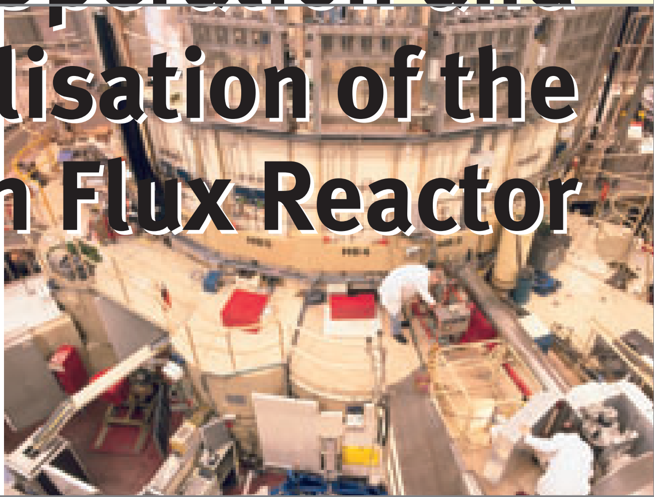
ISSN 1018-5593



Operation and Utilisation of the High Flux Reactor



Annual Report 2006

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Institute for Energy

EUR 22757 EN

Mission of the Institute for Energy

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.

European Commission
Joint Research Centre (DG JRC)
Institute for Energy
Petten
The Netherlands

Contact:

Tel. switchboard	+31-224-565656
High Flux Reactor	+31-224-565151
Public Relations & Communication	+31-224-565278

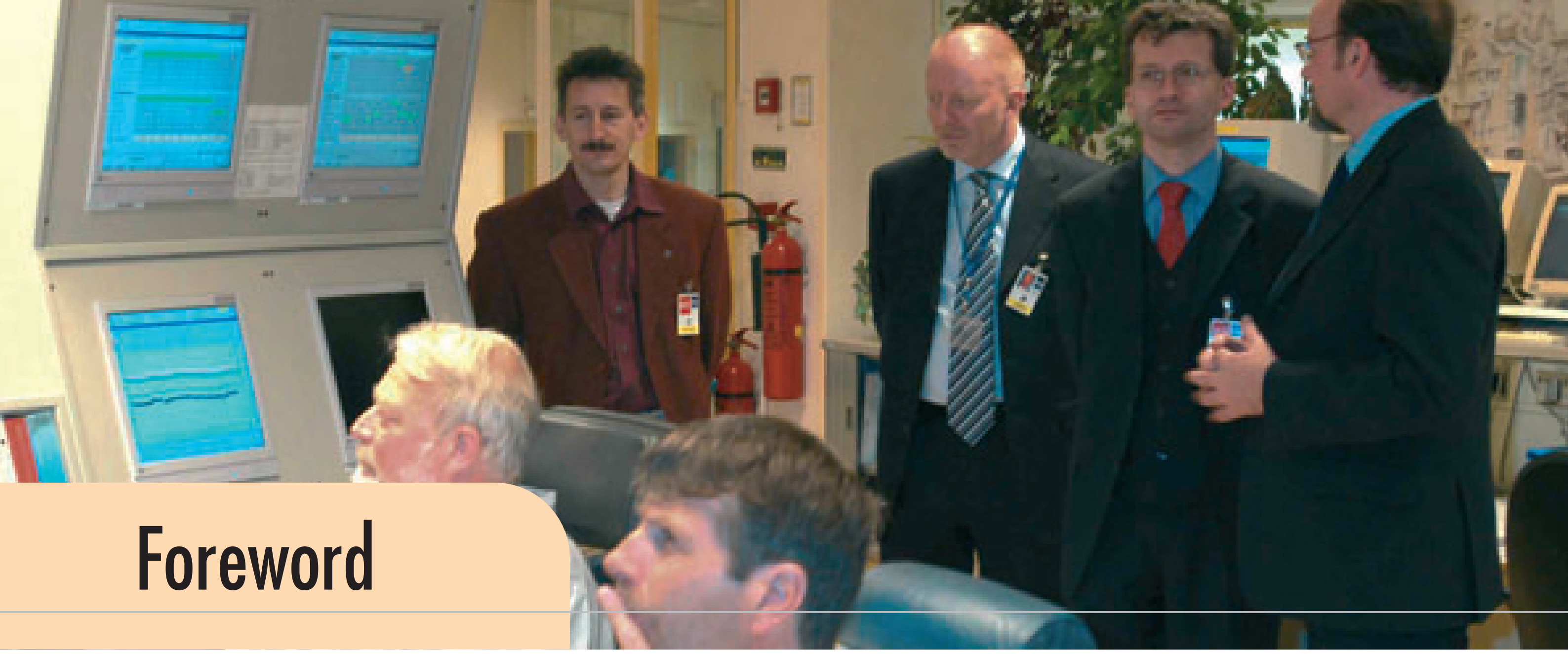
http://ie.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

Luxembourg: Office for Official Publications of the European Communities, 2007

ISBN 978-92-79-05568-3

Printed in the Netherlands, Aranea Offset B.V.

Table of contents



Foreword

In 2006, the High Flux Reactor has successfully confirmed its role as a key European nuclear research infrastructure. In line with its mission, the HFR has continued to provide valuable contributions in the research field of neutron material interaction in support of EU policies. The mission is deployed by optimal use of the reactor in the fields of:
- Nuclear safety of innovative reactors and existing reactors
- Health and environment
- Fusion energy
- Fundamental research

This includes participation in institutional and competitive activities as well as networking, training of young researchers and specific support towards new Member States.

An achieved, very high utilization factor of all irradiation positions and associated facilities is the result of the remarkable reliability of the HFR operation and of the highly qualified teams developing and supporting the experimental work.

In the area of nuclear fission, the scientific work in 2006 encompassed safety aspects of both existing and future nuclear reactors. The HFR has become a key player in establishing European best-practices for deterministic and risk-informed structural integrity assessment of key components, for all existing nuclear power plant designs. In 2006, R&D work has increased in the field of future nuclear power plants for the medium and the long term, focussing on the safety analysis and safety optimization of reactors, fuels and materials with improved sustainability and waste management features.

It has once more been demonstrated in 2006 that the neutrons produced at the HFR are essential for health. The development and exploitation of Neutron Capture Therapy at Petten has not only continued to perform clinical trials, but it has also intensified its research activities into dosimetry, treatment planning, radiobiology, boron compound testing and looking at other types of cancer, as well as non-cancerous diseases. The HFR has confirmed its position as the main producer of medical radioisotopes in Europe and is one of the main producers in the world. The supply of medical isotopes grew by more than ten percent in 2006, rising to a new record level.

The HFR's high versatility provides extremely relevant R&D capabilities, including fusion power plant technology. In 2006, the main areas of interest for irradiation experiments has been concentrated on the ITER vacuum vessel, the blanket development and the development of reduced activation materials.

On 6th May 2006, after more than 5 years of analyses, 10 years of irradiation tests, 3 years of licensing and a huge effort by a large number of staff, the HFR started operation with a fully Low Enriched Uranium core loading. This is a major achievement for the HFR: the conversion allows long term fuel supply and offers an important contribution to the global effort of diminishing the use of proliferation-sensitive High Enriched Uranium.

The year 2006 has also been a record year for environmental aspects. As a result of several shipments, more than 400 spent High Enriched Uranium fuel elements were removed from Petten, which is more than in any year before. The continuous improvements driven by safety culture have led to a thorough cleanup of the HFR pool, with the complete removal of high active waste originating from previous years of HFR operation.

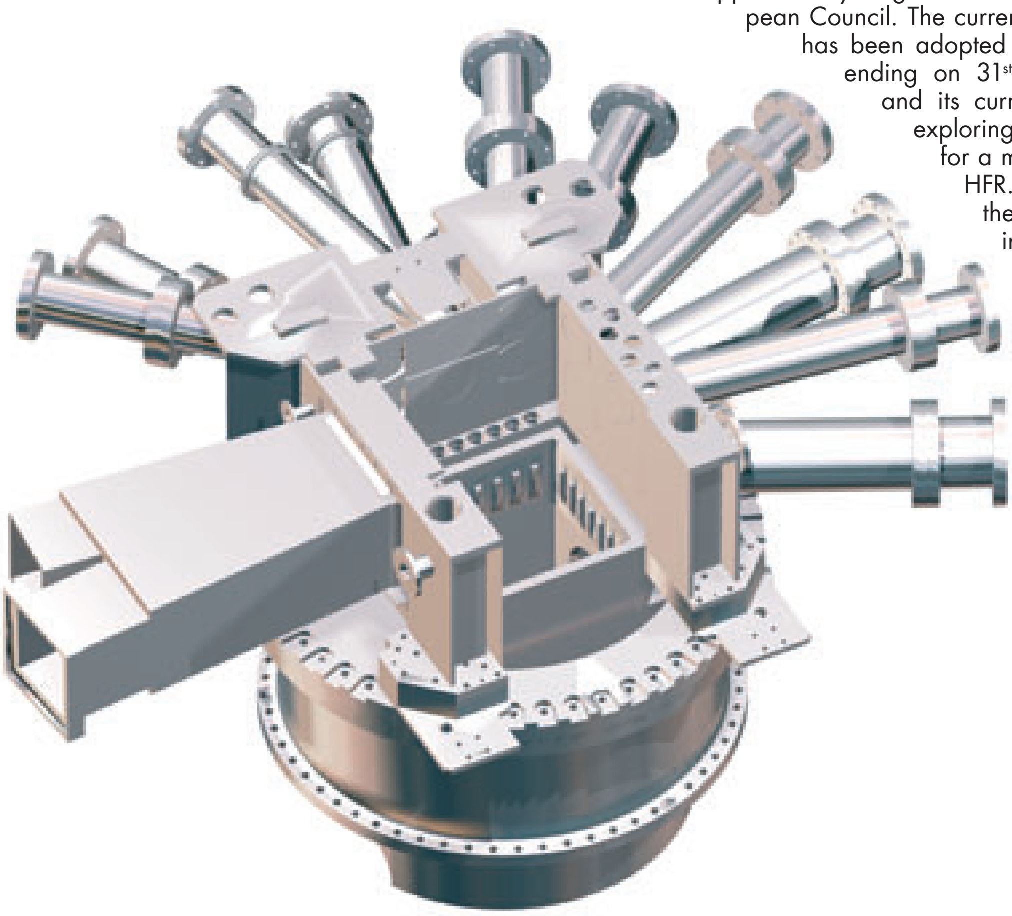
Finally, the management and staff of the HFR are pleased to provide this review of examples and highlights of their activities for 2006, and look forward to further fruitful cooperation with our many customers, partners, collaborators and interested parties.

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 examination 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, since the 2000/2003 programme, manages the commercial activities around the reactor. Since February 2005, NRG is the holder of the operating 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. This association between IE, NRG, TYCO, Urenco and hospitals leads to a Centre of Excellence, unique in Europe.

During the last three decades, the HFR has operated from Supplementary Programmes regularly discussed by the European Council. The current Supplementary Programme has been adopted for a period of three years, ending on 31st December 2006. The JRC and its current and future partners are exploring longer term engagements for a more sustainable future for the HFR. The objective is to broaden the partnership for the HFR and in particular to allow national and private research centres to join in the operation of the HFR.



HFR: Reactor Management

HFR Operation and related services

In 2006, the regular cycle pattern consisted of a scheduled number of 290 operation days and two maintenance periods of 24.3 days each. Besides regular maintenance and activities related to the modification project, the In Service Inspection of the bottom plug liner and the preparations for the shipment of 210 spent HEU fuel sections to the United States were successfully performed during the spring maintenance period. During the summer maintenance period, an extended reactor vessel In Service Inspection of the bottom plug liner and the yearly containment leak test, as well as several safety related modifications, were successfully performed.
In totality, the HFR was in operation for 280 days (Figure 1). This corresponds to an actual availability of 96.52% with reference to the original scheduled operation plan. Nominal power is 45 MW, with a total energy production of approximately 12,458 MWd, corresponding to a fuel consumption of about 16 kg ^{235}U.

Noteworthy, cycle-per-cycle highlights include: at the beginning of the reporting period, the HFR was in operation for the performance of cycle 05.12. The scheduled reactor start of cycle 06.02 was postponed to repair a leak of the primary heat exchanger. On request of the radioisotope producers, the 45 MW operation of cycle 06.02 was stopped two days later than originally planned. Cycle 06.04 started one day later then originally planned, due to a process/instrumentation problem with a flow indicator of the internal vessel wall cooling. During cycle 06.06, the reactor power was temporarily reduced to 42 MW, which was necessary to

Table 1 - 2006 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)
2006		MWd	hrs	h.min	h.min	h.min	h.min	h.min	h.min	PD*	Scram	Bq x E+11
01.01 - 10.01	05.12	410.55	224		224.00	00.05	224.05	15.55				
11.01 - 08.02	06.01	1176.68	640	04.05	640.10	00.10	644.25	51.30	0.05		1	3.8
09.02 - 12.03	06.02	1102.95	688	02.47	588.38		591.25	16.00	208.35	1		3.8
13.03 - 12.04	06.03	1167.96	664	01.59	622.41	02.00	626.40	68.20				3.6
13.04 - 05.05	Maintenance period							504.00				
06.05 - 04.06	06.04	1237.86	688	01.31	661.19		662.50	80.00	25.10			4.8
05.06 - 05.07	06.05	1233.42	664	02.21	657.58		660.19	80.00	03.41	1	1	3.9
06.07 - 06.08	06.06	1300.06	688	01.27	696.48	00.11	698.26	69.34				4.9
07.08 - 06.09	06.07	1243.59	664	03.22	662.23	01.41	667.26	76.34				4.4
07.09 - 29.09	Maintenance period and ISI							552.00				
30.09 - 29.10	06.08	1090.38	688	04.38	581.05		585.43	31.00	104.17		1	4.0
30.10 - 29.11	06.09	1209.48	664	02.19	648.57		651.16	80.00	12.44		2	4.0
30.11 - 31.12	06.10	1285.13	688	01.56	659.39	19.30	681.05	60.30	02.25	2		4.0
	TOTAL :	12458.06	6960	26.25	6667.38	23.37	6717.40	1685.23	356.57	4	5	41.2
Percentage of total time in 2006 (8760 h) :				0.3	76.11	0.27	76.69	19.24	4.07			
Percentage of planned operating time (6960 h) :				0.38	95.80	0.34	96.52					

**PD: Power decrease*

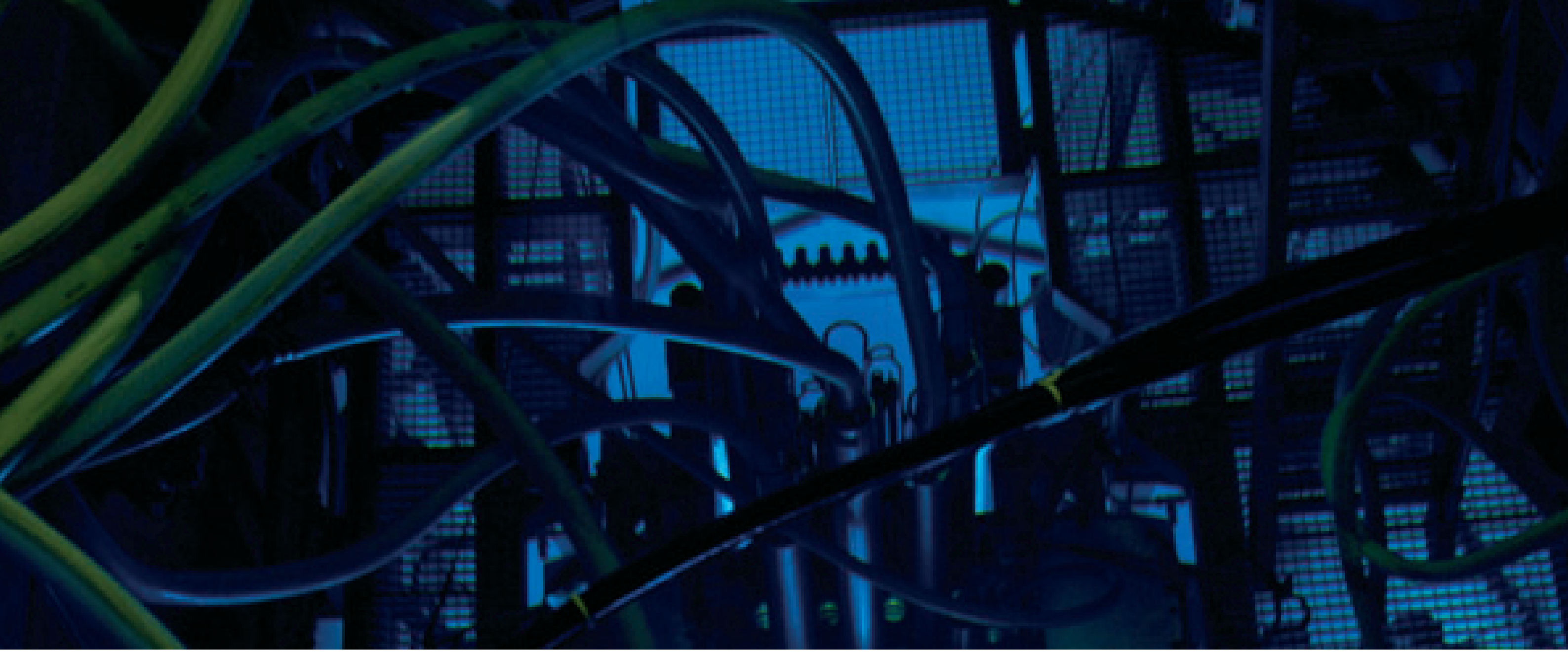


Figure 1 - HFR availability

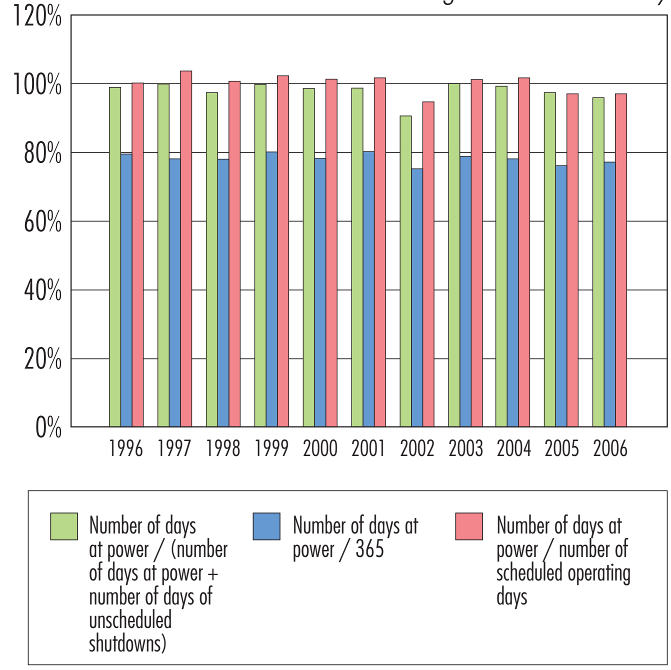
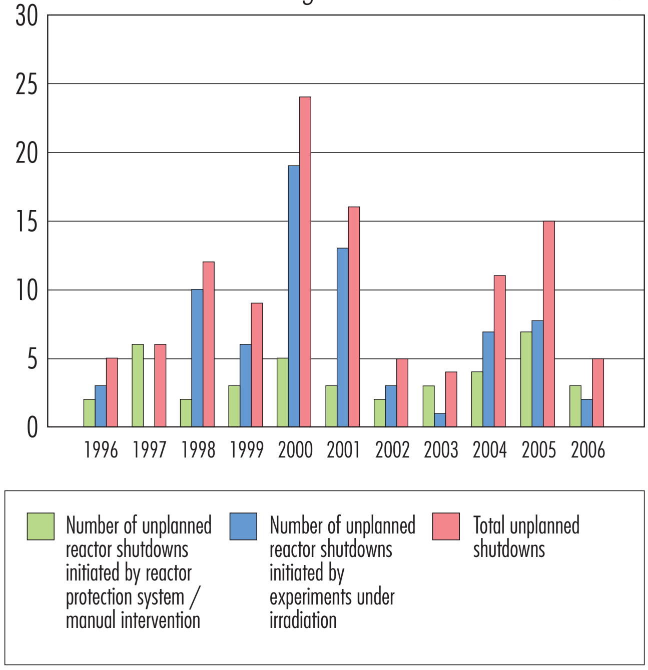


Figure 2 - HFR unscheduled shutdowns

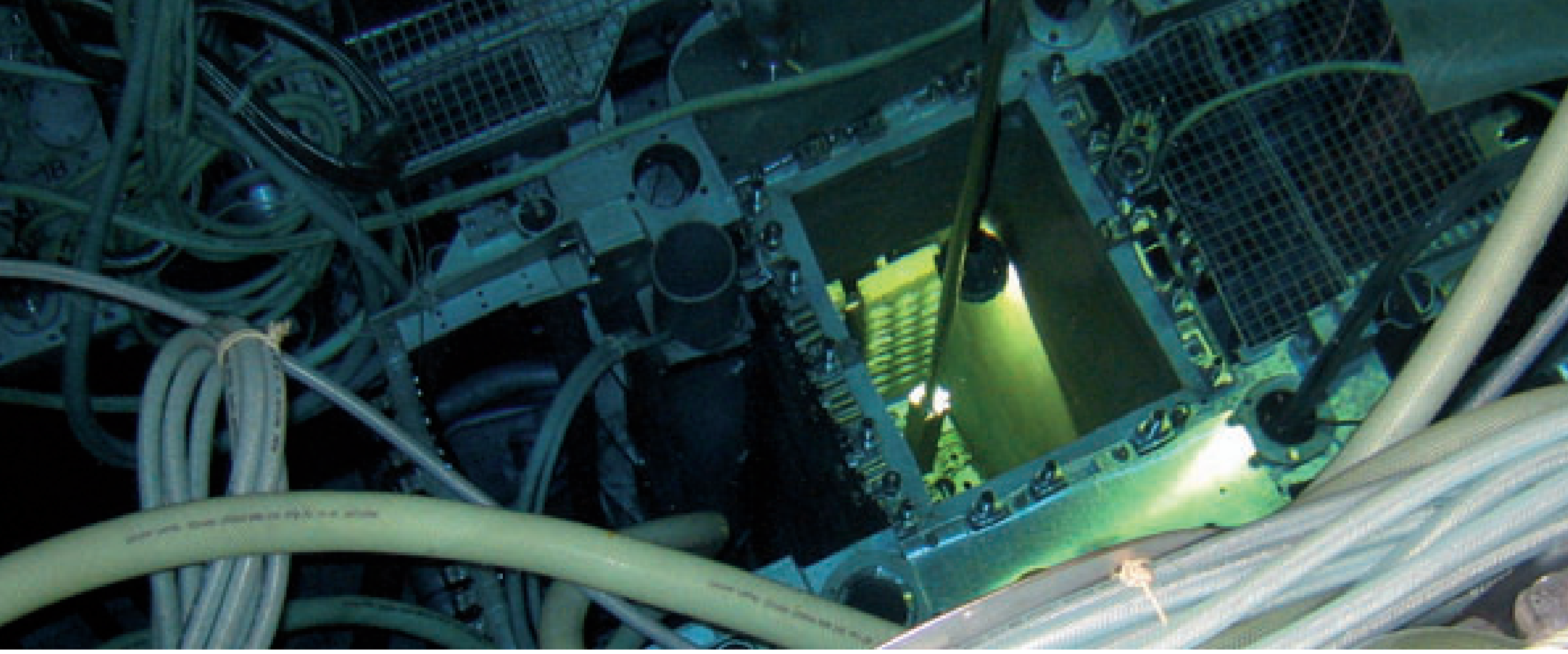


prevent exceeding of the allowed licensed outlet temperature (40°C) of the secondary coolant due to the extreme hot weather conditions in Europe. A manual reactor shut-down was necessary during cycle 06.08, to repair a leak in the newly installed bellow of the Accident Pressure Equalization (line "South") of the primary system. The reactor start of cycle 06.09 was delayed for more then 12 hours, due to a process/instrumentation setting, which occurred during the check-out prior to the start of the reactor.

During the reporting period two flux measurements at a reactor power of 500 kW in support of the HFR conversion programme were carried out. At the end of the year, the annual reactor-training programme at 30 MW was carried out. After the scheduled end of the 45 MW operation of each cycle, the shut-downs included activities performed in the framework of the regular HFR's operators training.

The detailed operating characteristics for 2006 are given in Table 1. All details on power interruptions and power disturbances are given in Table 2. It shows that five scrams occurred (see also figure 2). One of these scrams was due to human intervention, i.e. human mistake. Technical malfunctioning caused one scram, while another scram was caused by loss of off-site power. The remaining two scrams were due to intervention of the protection systems of the experimental devices.

In 2006, there were a high number of visitors to the reactor. Apart from the working visits of international colleagues and collaborators in the medical world, the open day during each cycle, attracted many visitors from the public. A total of 1,632 people, divided over 284 tours, were guided through the HFR facility.



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		
2005		hour	hour	hour	h.min	h.min						
26 Jan	06.01	17:40	17:45	18:45	00.05	01.05	AS	0	R	I	Cause unknown	Cause of RSA not traceable during reactor operation without jeopardizing safe and reliable operation, EIS will do measurements to trace the cause in the coming reactor shut-down period.
25 Feb	06.02	17:21	17:21	17:23	00.00	00.02	AP	27.5	R	H	Primary inlet temperature	During the back-flushing of the heat exchangers the primary inlet temperature exceeded its set-point with an automatic power decrease as result.
09 Jun	06.05	04:04		04:06		00.02	AP	38	R	H	Pool demin system	Due to changing over the pool demin pump from pool 2 to reactor pool an automatic power decrease occurred.
03 Jul	06.05	04:52	04:58	05:20	00.06	00.28	AS	0	R	E	Mains power supply	Loss of off-site main power supply causing a reactor scram
06 Oct	06.08	20:15					MS	0	A	M	Primary system	A manual reactor shut-down was necessary to repair a leak in the bellow of the Accident Pressure Equalisation line "South" of the primary system.
11 Oct			04:32	06:40	104.17	106.25						
07 Nov	06.09	05:58	06:08	06:33	00.10	00.35	AS	0	E	M	Coolant system	The coolant hose of the TYCOMO facility slipped off the connection, which caused an automatic reactor shut-down.
08 Nov	06.09	18:22	18:29	18:45	00.07	00.23	AS	0	E	M	Coolant system	The coolant hose of the TYCOMO facility slipped off the connection, which caused an automatic reactor shut-down.
05 Dec	06.10	16:10		16:11		00.01	AP	40.5	R	I	Pool cooling system	The reading of the reactor pool cooling F3 came for a moment just below the set-point with an automatic power decrease as result.
29 Dec	06.10	15:25		15:26		00.01	MP	36	E	S	267-06	Due to defective movement system of the trolley of PSF 6 a manual power decrease was necessary prior to the removal of the production facility MYKONOS 267-06.

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

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

Table 2 - 2006 full power interruptions of HFR

Fuel Cycle

Figure 3 - Spent fuel convoy prior to departure

Front end
During 2006, new Low Enriched Uranium (LEU) fuel elements and control rods were inspected at the manufacturer's site and delivered on schedule.

The conversion of the HFR from Highly Enriched Uranium (HEU) fuel to LEU fuel began in October 2005 and was successfully completed in May 2006 when the reactor started for the first time with a complete core of LEU fuel.

Back end
After the successful shipment of the spent, HEU fuel to the United States in 2005 preparations were started for a similar shipment in 2006. In April/May 2006, five transport containers were loaded with 210 spent fuel elements and transferred to the port of Den Helder for shipment to the US. In the first half of June, the spent fuel arrived safely at the Savannah River site.

During 2006, six spent fuel shipments to COVRA also took place. As in previous years, these shipments were performed using MTR2 containers. As a result of the shipments to COVRA and the shipment to the US, more than 400 spent HEU fuel elements were removed from Petten in 2006, which is more than in any previous year.

Also in 2006, new MTR2 baskets and spare parts were delivered. Furthermore, periodic inspections on a MTR2 container and on the MTR2 transport equipment were performed. Preparations were started for the removal of the remaining spent HEU fuel in the coming years.

Figure 4 - Loading of a cask for shipment to the US

Figure 5 - Absolute fluence rate values (n/cm²/s)

	604		A	B	C	D	E	F	G	H	I
		1									
	PSFW	2	2	3	1	1.85E+14 1.08E+14	4	9.29E+13 7.68E+13	2	6.60E+13 3.84E+13	
5	1.57E+14 2.80E+13	3	0	4	2.27E+14 1.45E+14	2	2.29E+14 1.22E+14	0	7.39E+13 8.78E+13	5	
6	1.38E+14 4.02E+13	4	1	0	5	3	6	4	1	7.69E+13 6.53E+13	
7	1.41E+14 4.25E+13	5	2	3	2.89E+14 1.67E+14	6	2.30E+14 1.37E+14	5	1.22E+14 9.95E+13	5	
8	1.35E+14 3.97E+13	6	1	1	6	2	6	5	0	7.45E+13 6.51E+13	
9	1.51E+14 3.02E+13	7	0	4	1.22E+14 1.53E+14	2	1.56E+14 1.26E+14	0	7.30E+13 8.89E+13	3	
10	1.28E+14 2.17E+13	8	2	3	1	1.72E+14 9.81E+13	4	1.19E+13 7.65E+13	1	6.25E+13 3.96E+13	
		9									

Beryllium | LEU Fuel element | LEU Control element | ΦThermal / ΦFast

ΦThermal = thermal (E < 0.625 eV) neutron fluence rate (n/cm²/s)
ΦFast = fast (E > 1.0 MeV) neutron fluence rate (n/cm²/s)

Figure 6 - Flux ratios LEU flux/HEU flux

	604 / 509		A	B	C	D	E	F	G	H	I
		1									
	PSFW	2				0.89 1.02		0.7 1.02		1.06 1.19	
5	0.96 0.9	3			0.89 0.95		0.86 0.95		0.78 1.07		
6	0.97 1.00	4								0.84 1.05	
7	1.00 1.04	5			1.05 0.89		0.81 0.83		0.8 0.96		
8	1.01 1.05	6								0.8 1.06	
9	1.05 1.11	7			0.91 0.96		0.85 0.92		0.78 1.12		
10	1.07 1.16	8				0.86 1.03		0.81 1.09		0.89 1.26	
		9									

Beryllium | LEU Fuel element | LEU Control element | Thermal flux ratio / Fast flux ratio


Visits and Visitors

January	20	Mr. Andris Piebalgs - Commissioner of Energy	1
February	02	Dr. Rob Adam - Director General South African Department of Science and Technology	2
March	02	Mr. Mikko Jokela - Finnish Ambassador	
	21	Prof. Krzysztof Jan Kurzydlowski - Polish Vice Minister of Education and Science	
	30	Borough Council of Heerhugowaard	
May	08	Celebration conversion to low enriched uranium HFR	
	16+18	Visit to HFR by students of the 7th year (with option physics) of the European School	
June	01-02	Visit of Russian BNCT Group to Petten	
	29	Mr. Emmanuel Horowitz, attaché at the EdF Nuclear Engineering Division which is responsible for the design of Gen III and Gen IV type reactors.	
October	20	Joint ECN-NRG visit of representatives from Local Government in North Holland	
November	17	Joint IE-ECN-NRG Visit of Mayors and representatives from six local councils	
December	19	Mrs. Megan Richards - Director of Programme and Resource Management	

Workshops and seminars

June	06-08	Seminar Safety of Russian design nuclear power plants
November	28-30	JRC-IAEA International Workshop on In-Service Inspection Qualification Bodies
	29-30	The 3rd NET-PECO workshop on Industrial R&D, Material properties and stress/strain measurements, neutron methods for engineering applications and residual stress modelling
December	07-09	E&I Workshop: "Innovative Treatment Concepts for Liver Metastases", held at University Hospital Essen, with presentations by clinicians covering all treatment modalities for liver cancer, including BNCT

HFR: The Programmes

HFR as a Tool for European Programmes

EUROPEAN NETWORK AMES AND SAFELIFE

The JRC project SAFELIFE provides an integrated approach to research and development on safety issues for plant life management of ageing nuclear power installations.

The project focuses on establishing European best-practices for deterministic and risk-informed structural integrity assessment of key components considering all nuclear power plant (NPP) designs (both western and Russian). It exploits IE's competence in testing and characterisation of materials degradation (radiation embrittlement models development, thermal fatigue, stress corrosion cracking), structural mechanics, non-destructive testing & In-Service Inspection (ISI) qualification, neutron methods and advanced modelling techniques for residual stress analysis, as well as developing appropriate new areas of expertise.

The activities in 2006 were organised following key primary circuit components: reactor pressure vessel, primary piping, core internals and their weldments.

In addition to these component-specific activities, further activities covered method development on more generic topics supporting decision making in life management, namely: uncertainty management, maintenance optimisation, human factors and safety culture issues and risk-informed approaches. Active components are included in the scope of the maintenance optimisation tasks. SAFELIFE systematically uses the available capabilities to actively support advanced reactor materials research and advanced analysis, e.g. behaviour of materials under high loading rates.

Figure 7 - AMALIA (Assessment of Nuclear Power Plant Core Internals)

SAFELIFE continues to support European Networks and training activities within the frame of ERA. It will also continue a proactive policy for the integration of experts and organisations from New and Member States, Candidates Countries and neighbouring Countries in its activities.

The strategic multi-annual goals of the Action are as follows:

- Provide a basis for harmonisation of European codes and standards on key primary components of light water reactors through developing and disseminating best practices;
- Support long-term EU policy needs on PLIM and advanced reactor concept through enhancing JRC R&D competence and capabilities in nuclear safety technology;
- Integration of R&D efforts in line with ERA principles by linking our R&D to utilities, manufacturers, R&D organisations and regulators through continuing exploitation of networks and collaborating with EC and international organisations;
- Implementation of an effective plan for training, mobility, dissemination and knowledge management and development of competitive activities complementary to SAFELIFE objectives.

A series of tasks directly address radiation embrittlement to improve understanding of reactor pressure vessel integrity issues, with emphasis on material characterisation, radiation embrittlement understanding, fracture toughness and application of probabilistic approaches for structural reliability analysis. The tasks are mainly co-ordinated within the frame of the AMES European Network.

The tasks are addressed as follows: irradiation of different RPV steels in the LYRA rig at the HFR, studies on non-destructive measurements of cladding radiation embrittlement (irradiated in the HFR), based on ND methods, such as the STEAM method and Barkhausen Magnetic method, for the characterisation of materials, as well as for IAEA International Benchmarking projects (model alloys, model steels and realistic welds projects). Other studies include inter-granular fracture, characterisation of materials for future vessels (Cr-Mo-V based alloys), support to large international projects such as PERFECT and COVERS, etc.

Recent irradiations and results

A new irradiation campaign in the LYRA rig was performed to study materials taken from WWER reactors during

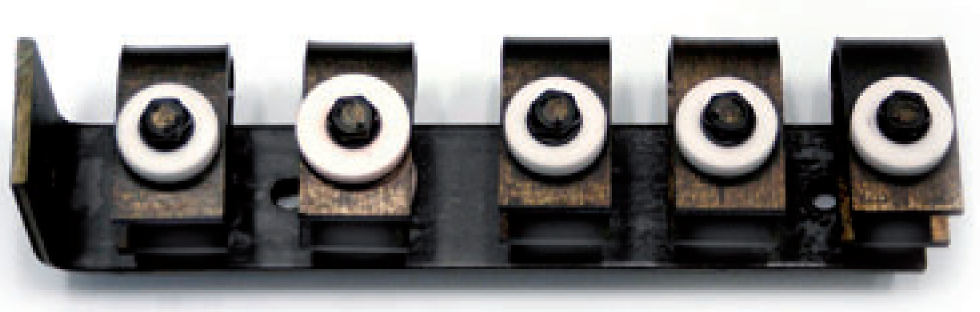


Figure 8 - Typical U-band samples for Stress Corrosion Cracking (SCC)

decommissioning in Germany. The results, together with results from recently analysed projects, such as the FRAME and PISA projects, where irradiations in the HFR of samples representative of both western and Russian-type reactor systems were carried out, are supporting the validation for irradiated materials of novel methods for structural integrity: the master curve methodology, in particular.
LYRA is now celebrating 10 years of continuous operation, proving to be a robust JRC design, useful, reliable, easy to use and a versatile unique facility producing high quality irradiation results. The next irradiation programme will be dedicated to the quantification of the effect of Mn on radiation embrittlement for both welds and base metals of pressurised reactor systems.

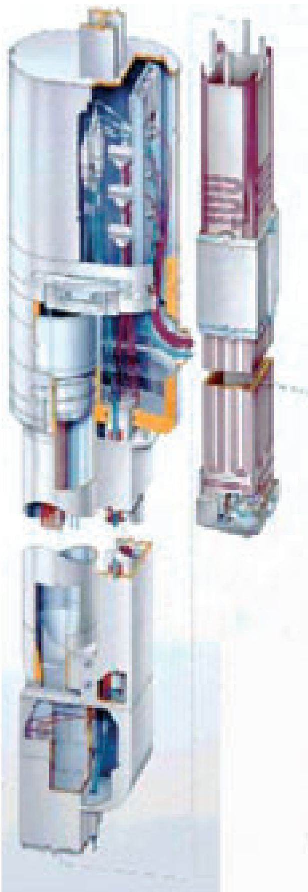


Figure 9 - LYRA irradiation rig

LYRA rig: 10 years of succesful operation

LYRA I	REFEREE - Nuclear Electric	190°C, 11.5x10^{22} m^{-2}	Terminated
LYRA II	RESQUE / SCK	255°C, 8.17x10^{22} m^{-2}	Terminated
LYRA III	MODEL ALLOYS/JRC	270°C, 6.11x10^{22} m^{-2}	Terminated
LYRA IV	PISA I/British Energy	200°C, 5x10^{22} m^{-2}	Terminated
LYRA V	FRAME/VTT	280°C, 20x10^{22} m^{-2}	Terminated
LYRA VI	PISA II/British Energy	290°C, 5x10^{22} m^{-2}	Terminated
LYRA VII	PISA III/British Energy	290°C, 18x10^{22} m^{-2}	Terminated
LYRA VIII	NRG irradiation	HTR materials	Terminated
LYRA IX	VVER-440/FZR	265°C	Unloaded end 2006
LYRA X	Model Steel/JRC	290°C	Terminated

IASCC loop in the HFR
The design of a new IASCC (Irradiation Assisted Stress-Corrosion Cracking) loop for the HFR is progressing. The design is based on the experience on SCC built-up in recent years with the out-of-pile SCC loops, such as AMALIA, see Figure 7. The loop will be unique in its type and will help in solving the critical issue of demonstrating and quantifying the effect of irradiation on stress-corrosion processes for BWR, PWR and VVER reactors systems as well as future systems (SCW, super-critical-water).

SAFETY OF INNOVATIVE REACTOR DESIGNS (SAFETY-INNO)

The institutional action "Safety of Innovative Reactor Designs" (SAFETY-INNO) carries out R&D related to future nuclear power plants for the medium and the long term including several ongoing FP5 and FP6 indirect actions. The tasks focus on the safety analysis and safety optimization of reactors, fuels and materials with improved sustainability and waste management features. In 2006, the action comprised the following:

- Activities related to the High Temperature Reactor Technology Network;
- Fuel Irradiations for High Temperature Reactors and Transmutation;
- Structural material out-of-pile tests for innovative reactors;
- Safety and feasibility studies on innovative reactor concepts;
- Exploratory research on energy efficient power conversion methods and use of process heat.

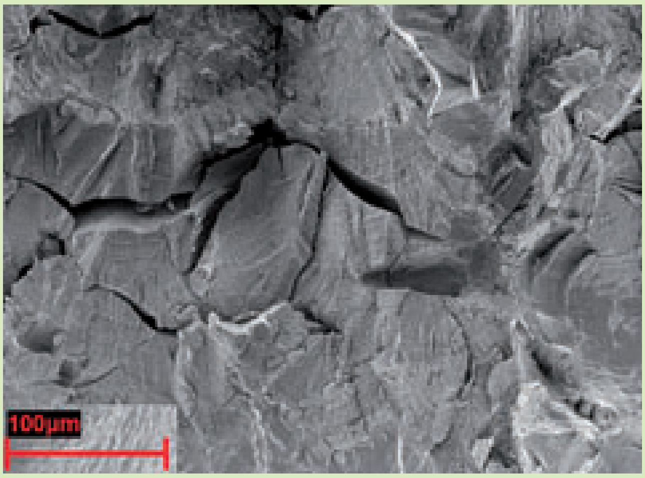


Figure 10 - SCC methodology

HIGH TEMPERATURE REACTOR TECHNOLOGY NETWORK - HTR-TN

Background

In response to growing interest in HTRs worldwide and on the initiative of JRC, HTR-TN was established in April 2000 to recover, maintain and develop HTR technology from Europe and elsewhere. The ultimate goal is the development of advanced HTR technologies thus supporting industry in the design of power plants, which comply with stringent requirements in terms of sustainability, economic competitiveness, safety, waste production and social acceptability.
Since its creation, HTR-TN has performed very successfully and contributed to an efficient EU-wide exchange, including the organization of specialist meetings, seminars and conferences. Further information can be found at www.jrc.nl/htr-tn.

Achievements in 2006

JRC-IE is the operator of the HTR-TN network and contributions to the coordination of related projects and provides technical input through both institutional and competitive actions. HTR-TN is driven currently by 21 partners and two observers from research and industry, with several new companies having applied for participation in 2006.
The network partners efficiently coordinated and supervised the execution of several HTR-related R&D projects within the EU's FP5 and FP6, and started preparation of related project proposals for the 7th Framework Programme.
Much of JRC-IE's technical achievements within HTR-TN were proposed as Euratom input to the related Generation IV International Forum (GIF) projects. Several HTR-TN partners, including the JRC, are members of high-level GIF bodies and of GIF project management boards. After clarification of Intellectual Property exchange, several of these projects are expected to be signed in 2007.
Particular highlights of HTR-TN activity were the contributions to the very successful organization of the HTR 2006 conference in Johannesburg, South Africa in October 2006 (http://htr2006.co.za/). The quality of papers was of a very high standard, and participation and press response were unparalleled. The next venue will be Washington DC, USA in September/October 2008.

Figure 11 - Autoclave for Stress Corrosion Cracking (SCC)

NETWORK ON NEUTRON TECHNIQUES STANDARDISATION FOR STRUCTURAL INTEGRITY (NET)

NET supports progress in performance and safety of European energy production systems. The partners have established three Task Groups (TG) dealing with the assessment of welding stresses and the impact of thermal ageing on certain steels. During 2006 the NET Steering Committee met twice (Figure 12). In November 2006, an enlargement and integration workshop was organized focusing on Small Angle Neutron Scattering. Twenty scientists from seven member states plus Russia and Turkey participated.

Figure 12 - 10th NET Steering Committee Meeting, Petten 30 Nov - 1 Dec 2006

NET work programme development and execution

- ***TG1 - Single Bead on Plate Weld***
  The purpose of this Task Group is to perform, experimentally and numerically, a thorough assessment of the residual stress field around a single weld bead on a steel plate. British Energy issued a report on the results of phase 1 of TG1 in 2006. Based on the findings, an updated problem definition for new analyses (phase 2) was established and several analyses have been completed (see example in Figure 13). A dedicated issue of the International Journal of Pressure Vessels and Piping with 14 contributions has been submitted.
- ***TG2 - Assessment of post-weld stress relief heat treatments***
  TG2 has established an auxiliary round robin exercise with a ferritic steel plate with three weld beads filling a groove of 9 mm depth. Numerical stress analysis is used for this problem. Based on an agreed problem definition the first numerical analyses have been performed (see Figure 14). Residual stresses have been mapped with high resolution across a full cross section of the specimen by the contour method.
- ***TG3 - Assessment of effects of thermal ageing in duplex stainless steels***
  While JRC-IE and INR-Pitesti (RO), have (re-)commissioned their SANS facilities, additional NET partners have offered contributions to NET TG3, i.e., Frank Laboratory for Neutron Physics, Dubna (RUS), ENSAM (F), National Institute for Material Physics (RO).

NET related shared cost activities

INTERWELD - Investigation of irradiation induced material changes in the Heat Affected Zones of Reactor Pressure Vessel welded internals: After installation of a shielded facility, measurements of residual stresses were performed in irradiated welded specimens.

Other NET activities

In 2005, a contract for third party work had been signed for residual stress investigations in welded nuclear components. Measurements on a first component were completed in 2006, while work on the second component is ongoing.
An IAEA driven Collaborative Research Project on research reactors and their residual stress measurement capabilities had its kick-off meeting in 2006. The project aims at enhancing the utilization and performance of existing facilities, in particular in developing countries.
A Technical Meeting on Specific Applications of Research Reactors in Development, Characterization and Testing of Materials was organized by the IAEA in Spring 2006. The NET team made a contribution and the meeting proceedings have been published in the form of an IAEA-TECDOC.

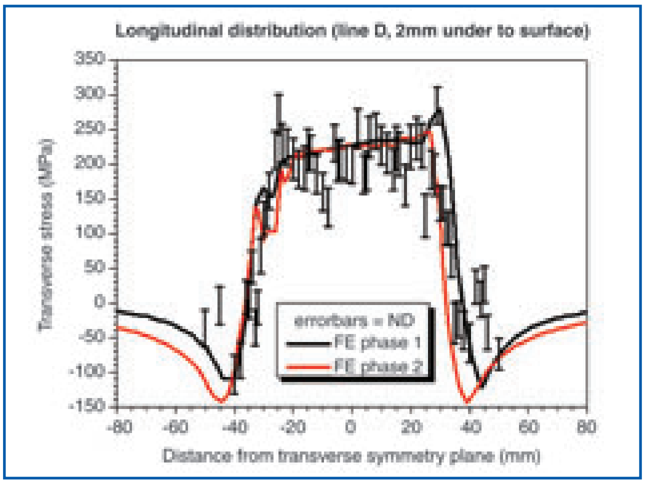


Figure 13 - NET TG1: Comparison of JRC-IE neutron diffraction residual stress measurements with modelling data obtained in both phases of the numerical round robin exercise by University of Patras

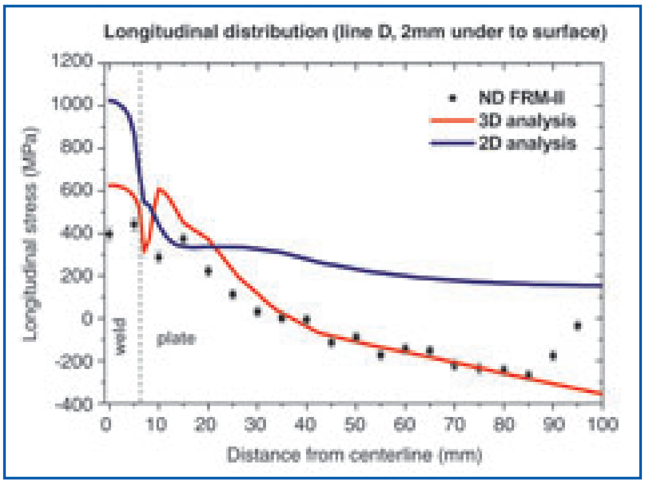


Figure 14 - NET TG2: Comparison of neutron diffraction residual stress measurements (TU-Munich-FRM II) with modelling data obtained by 2-D and 3-D numerical analyses by University of Patras

HFR as a Tool for Research

NEUTRON BEAM RESEARCH

In 2006, the HFR Unit has continued its efforts to upgrade and revitalize the neutron beam facilities at the High Flux Reactor. Modifications and upgrades have been made at the Neutron Radiography facility at beam tube HB8 and the Small Angle Neutron Scattering facility at beam tube HB3b.
The NEU-DI-CIWI facility for residual stress analysis at HB4 has been decommissioned after the successful execution of the residual stress analysis in welded irradiated steel specimen in the context of the INTERWELD project. Subsequently, the Large Component Neutron Diffraction Facility has been re-installed.
Finally, installation work at the new residual stress diffractometer at beam tube HB5 continued throughout the year.
As a consequence of these upgrading and renovation activities, only a very few residual stress measurement campaigns could actually be performed in 2006 at the HFR. Details on one of these campaigns is given below.

The NEU-DI-CIWI facility at beam tube HB4

In 2005, the NEU-DI-CIWI facility has been installed in place of the Large Component Neutron Diffraction Facility in front of beam tube HB4 (Figure 15). This facility was dedicated to residual stress analysis in irradiated components relevant to nuclear power applications. Its dominant feature therefore was the presence of heavy lead shielding in order to protect workers and visitors at the HFR from the radiation emanating from the test pieces under investigation.
Residual stress measurements in welded steel specimens previously irradiated at the HFR (CIWI-01 and CIWI-02) in the context of INTERWELD, were performed at this facility in 2006. The main objective for these measurements was to shed light on the influence of neutron irradiation on the evolution of residual stress levels in these steel welds representative of core shroud welds of existing light water power reactors. The goal was very innovative and the experience gained by the JRC staff in measurements of radioactive specimens was indispensable. The specimens, welded bars made from austenitic steel grade SS347, had previously been measured as non-irradiated, virgin specimens. At the new shielded facility, measurements were taken from test coupons irradiated to two different dose levels, i.e. ~0.3 dpa and ~1 dpa, corresponding to four and 11 reactor cycles, respectively. Strict procedures for the execution of these measurements had been established to ensure that workers and visitors at the facility would not be subjected to unnecessarily high radiation doses through these experiments.
The comparison of the measurement results obtained from the irradiated welds against earlier measurements on the virgin companion specimen suggested that substantial relief of residual stresses by irradiation had taken place near the specimens' surface. On the other hand, residual stresses found at mid-thickness were apparently not affected by long-term irradiation (Figures 16 and 17). Unfortunately, conclusions could not be drawn concerning the impact of irradiation duration. The suspicion is that, due to a local deviation of the test specimen subjected to the short-term irradiation, this specimen had exhibited lower residual stresses from the very beginning. However, the available data do not suffice to corroborate or disprove this assumption.
After the successful execution of the measurements in irradiated steel specimens, the NEU-DI-CIWI facility was disassembled again and the Large Component Neutron Diffraction Facility was reinstalled at beam tube HB4. Both facilities in the future can be exchanged in accordance with the needs. However, the related effort is substantial, which makes further development of the NEU-DI-CIWI facility indispensable for future projects.

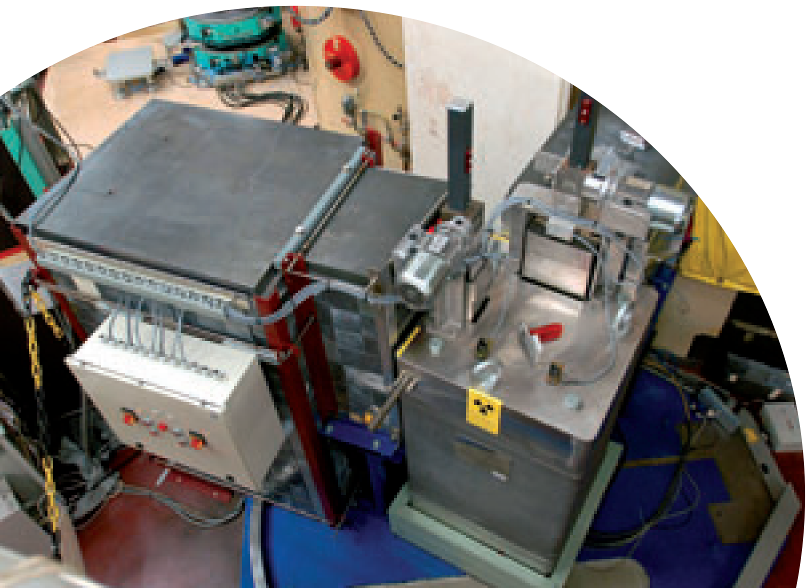


Figure 15 - Top view of the HB4 experimental set-up, the NEU-DI-CIWI facility, for residual stress analysis in irradiated weld specimens based on neutron diffraction

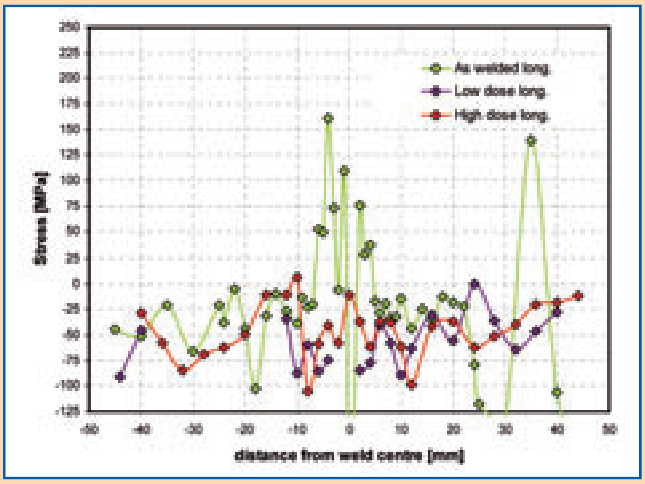


Figure 16 - Longitudinal residual stresses measured close to the surfaces of irradiated and non-irradiated weld coupons (INTERWELD)

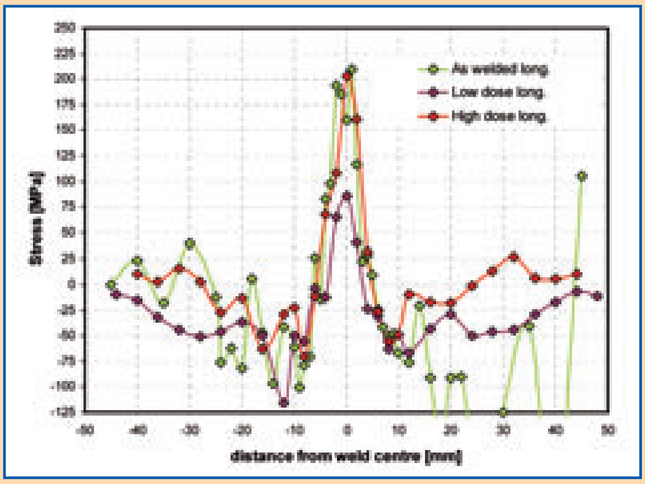


Figure 17 - Longitudinal residual stresses measured at mid-thickness of irradiated and non-irradiated weld coupons (INTERWELD)

New facility at HFR/HB5: VISA - the Versatile Instrument for Stress Analysis

Work on the installation of the new residual stress diffractometer at beam tube HB5 continued throughout the year 2006. The mechanical system of the new diffractometer, which had been delivered in late 2005, has been installed on the new polished floor. The cabling of all motors, encoders and control units has been completed and the functioning of the mechanics was tested by using a first level control software. Subsequently, the neutron detector and its housing were installed and tested and the development of the new instrument control and measurement software was started.
The new instrument will facilitate handling of much larger specimens in a much more flexible way than the old diffractometer at HB5. Specimens of up to 200 kg can be placed and the movement range of the sample positioning tables is now 250 mm instead of 100 mm. It is now possible with this installation, entirely moveable on air pads, to use the second available beam exit, so that a very different neutron wavelength can be employed (Figure 18).

HFR Neutron Radiography Facility at beam tube HB8

The HFR neutron radiography facility was completely refurbished and re-commissioned in 2005. Refurbishment of all vacuum and cooling installations of the neutron beam filter units, the process monitoring equipment and the gas and vacuum seals was performed. With a series of test exposures, the facility has been put back into operation delivering radiographs of high quality. During these commissioning tests the level of background gamma-radiation around the camera station was found to be unacceptable with respect to the new legislation in radiation acceptance.
It was decided to install a new camera station, incorporating a substantial amount of lead shielding in order to reduce the gamma background dose rate during exposures by a factor of 10. The new camera station, offering amongst others a lead shielding thickness of 5 cm, completely surrounding the camera and the object under investigation, was constructed and installed in 2006. Subsequent tests have shown that a substantial reduction of the gamma background dose rate has been achieved with an actual factor reduction of 20x.

HFR Small Angle Neutron Scattering Facilities Development

Small Angle Neutron Scattering (SANS) is a technique used for characterizing sizes (size distributions) and shapes of inhomogeneities in materials and in their mutual interactions. Applications in material science include: nucleation and growth of precipitates and voids, characterization of distributed damage in metals and ceramics as a result of creep and fatigue, microstructural changes after heat treatment and porosity of materials. SANS is currently emerging as a powerful non-destructive method for the investigation of irradiation and thermal ageing induced damage in steel alloys.

The current SANS facility at beam tube HB3b has characteristics comparable to those of other European SANS instruments with pinhole geometry. Concerning the scattering vector **Q**, most facilities operate in the range 10^{-3} to 0.4 $Å^{-1}$. The SANS facility at the HFR has a range of accessible **Q** values between 5 x 10^{-3} and 0.4 $Å^{-1}$, and this range covers well the values 10^{-2} - 0.4 $Å^{-1}$ usually needed for investigation of irradiation defects. The accessible size range for the SANS facility is roughly 1-100 nm.
However, the neutron flux at the current SANS is about 10^4 $cm^{-2}s^{-1}$, which constitutes a relatively low flux. Its neutron wavelength is fixed at 4.75 Å. For these reasons, a development project has been initiated in 2003 for the construction of a new SANS facility at the HFR. Based on the proposed upgrade, it is expected to achieve a neutron flux in the order of ~10^6 $cm^{-2}s^{-1}$ as available at most similar facilities in Europe. In addition, the envisaged upgrade will give access to a much larger range of long wavelengths.

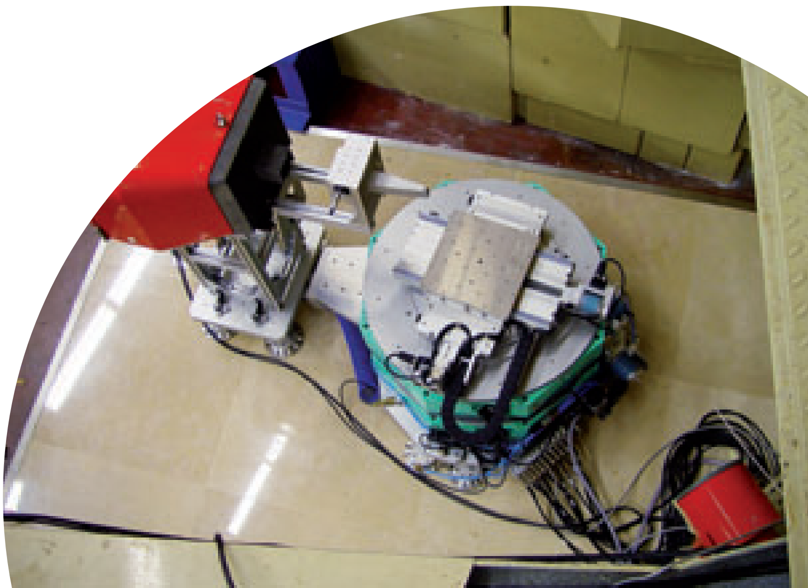


Figure 18 - HB5: new diffractometer for residual stress analysis (VISA) installed on the polished 'Tanzboden' floor

Figure 19 - The new Imaging-station at 11 meter from the HFR-core

This upgrade of the SANS facility should allow for the investigation of defects in a large class of cases, including irradiated material specimens. This capability, coupled with the HFR irradiation facilities and the new LCNDF version for neutron diffraction on irradiated specimens, would result in a unique and autonomous Combined HFR Laboratory for characterization of RPV welded internals within Europe.

Re-commissioning of the current SANS facility at HB3b

The Small Angle Neutron Scattering (SANS) facility at the HFR was developed and built in the late 80's to early 90's within the context of the then ECN research activities on solid state physics. After having been idle for more than 10 years, some of the equipment at the facility has been found to be obsolete. Other parts were simply not functioning anymore. A lot of the obsolete equipment has been replaced in 2005 and 2006. Most of the non-functional equipment has been replaced. Calibration and alignment of the instrument has been performed and several measurements with known test pieces have been executed to establish the correct functioning of the instrument (see example in Figure 20). In parallel to the first investigations on specimens with material defects, the upgrading work on the facility continues to constantly improve its performance and to modernize the equipment.

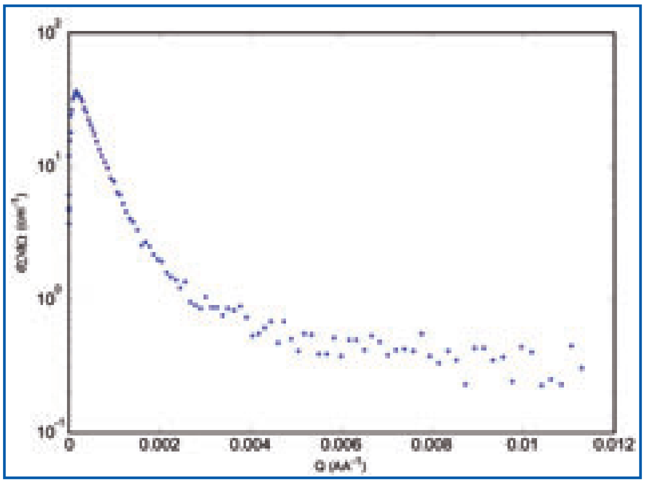


Figure 20 - SANS scattering from 2.5 vol. % polystyrene spheres in water used for calibration of the instrument. The radius of the spheres, based on a Guinier fit of the data, is 103.7 Å. The manufacturers specification in this case is 105 Å

NEW SANS FACILITY AT HB10

Objectives/Applications

The main objective of the new SANS facility is to develop the capability to efficiently analyze radiation, thermal ageing and fatigue induced damage in welded steel alloy materials in the context of the SAFELIFE Action and the NET European Network. In addition, it is expected to contribute to investigations related to innovative reactor concepts, including fusion technology, and to other activities of JRC-IE, for example hydrogen storage materials.

Outline of design concept

The restrictions of the existing SANS facility at beam tube HB3b have been found to be insurmountable with a facility confined to the perimeter of the HFR containment. For this reason, beam tube HB10 has been chosen for the new SANS facility because it offers the highest entry neutron flux and downstream of HB10, a new building can be erected to house the new facility.

The original concept included a beryllium based cold neutron source near the reactor in order to shift the neutron spectrum in the beam to the desired low energies. The neutrons were then to be guided to the facility through a neutron guide installation facilitating the transport of neutrons over a large distance with very limited loss in flux. The necessary shielding of the beam will be accomplished using lead and concrete. A neutron velocity selector will give access to wavelengths in the range 5-20 Å, which, together with a detector vacuum chamber significantly longer than the present one, will significantly enhance the Q-range accessible by this facility. Finally, a new collimator will be installed for optimum resolution.

The new facility will be housed in a dedicated new building. This building will be designed to allow for handling and storage of shielded equipment, such that investigations of irradiated specimens are possible by both SANS and neutron diffraction. In case the JRC would decide for this further development in the future, the building will provide room for later installation of an additional neutron scattering facility. Based on these proposals, a unique combination of advanced experimental facilities, aiming at the assessment of irradiation impact on welded nuclear safety related specimens, representative of RPV internal components, both in terms of residual stress and defects evolution, will become available.

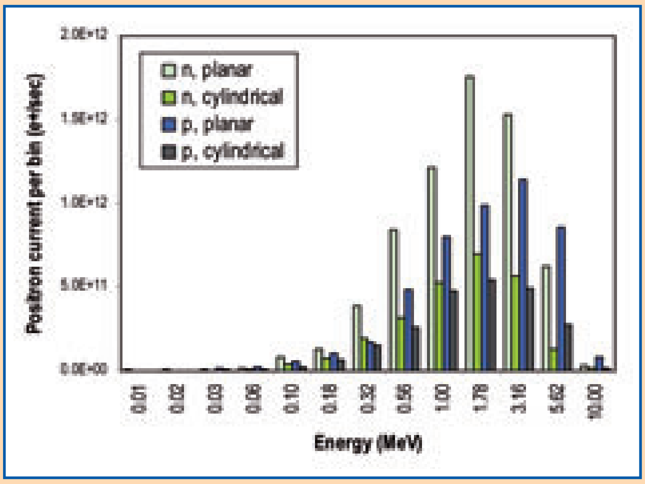


Figure 22 - Energy spectrum of positrons (forward direction)

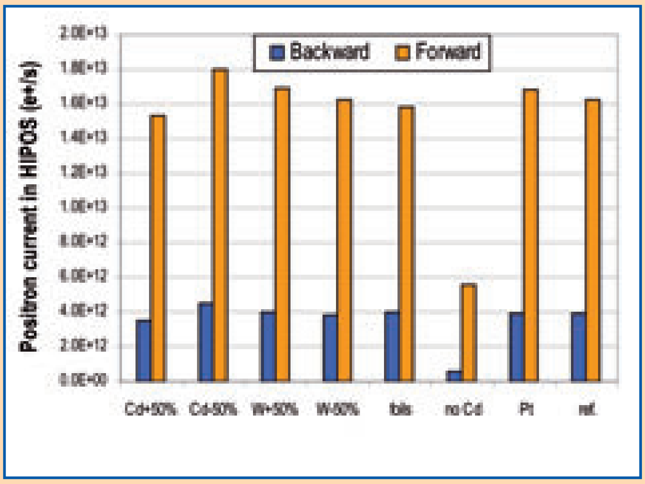


Figure 23 - Material optimization of the positron generator

Progress in 2006

In 2006, the performance analyses of the Be based cold neutron source and the neutron guide system have been undertaken. Unlike as previously expected, these analyses have shown that the proposed cold neutron source could not deliver the expected gain factor of 6 for the neutron flux at about 5 Å. It was subsequently decided to pursue this development without a cold neutron source, as the achievable low flux gain did not justify the investment. Preliminary analyses suggested that even without the cold source, the new facility could provide a neutron flux nearly two orders of magnitude higher than the existing facility at the HFR. A modified solution for the neutron guide has been proposed after the analyses, which would give significant advantages for the amount of beam shielding needed and for the size of the SANS facility itself. Analyses concerning the feasibility for such modifications are underway.

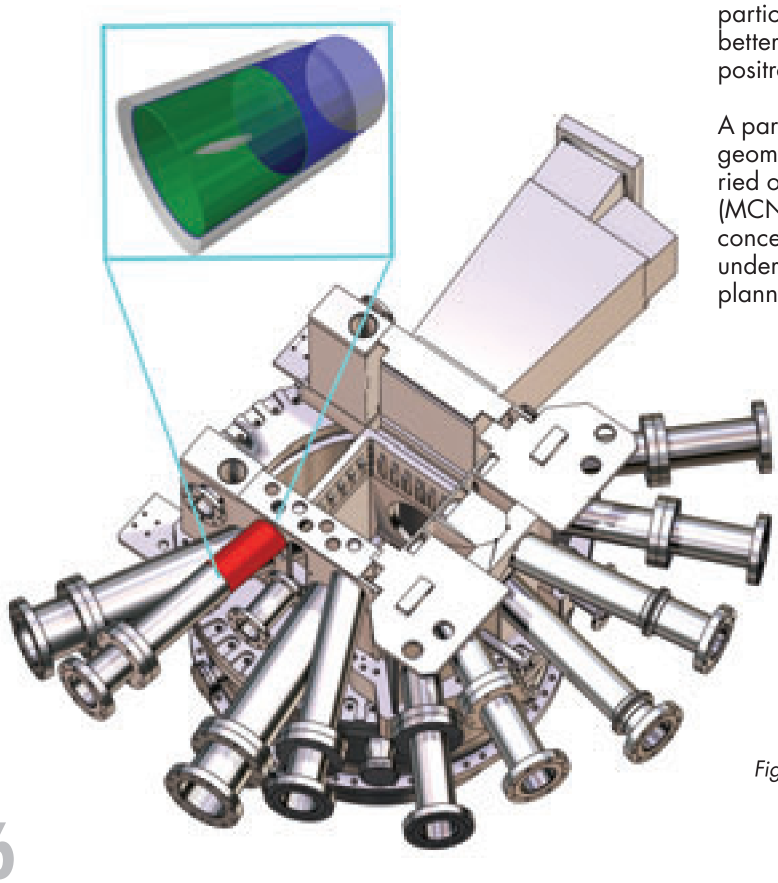


Figure 21 - Position of positron generator at HFR-HB9

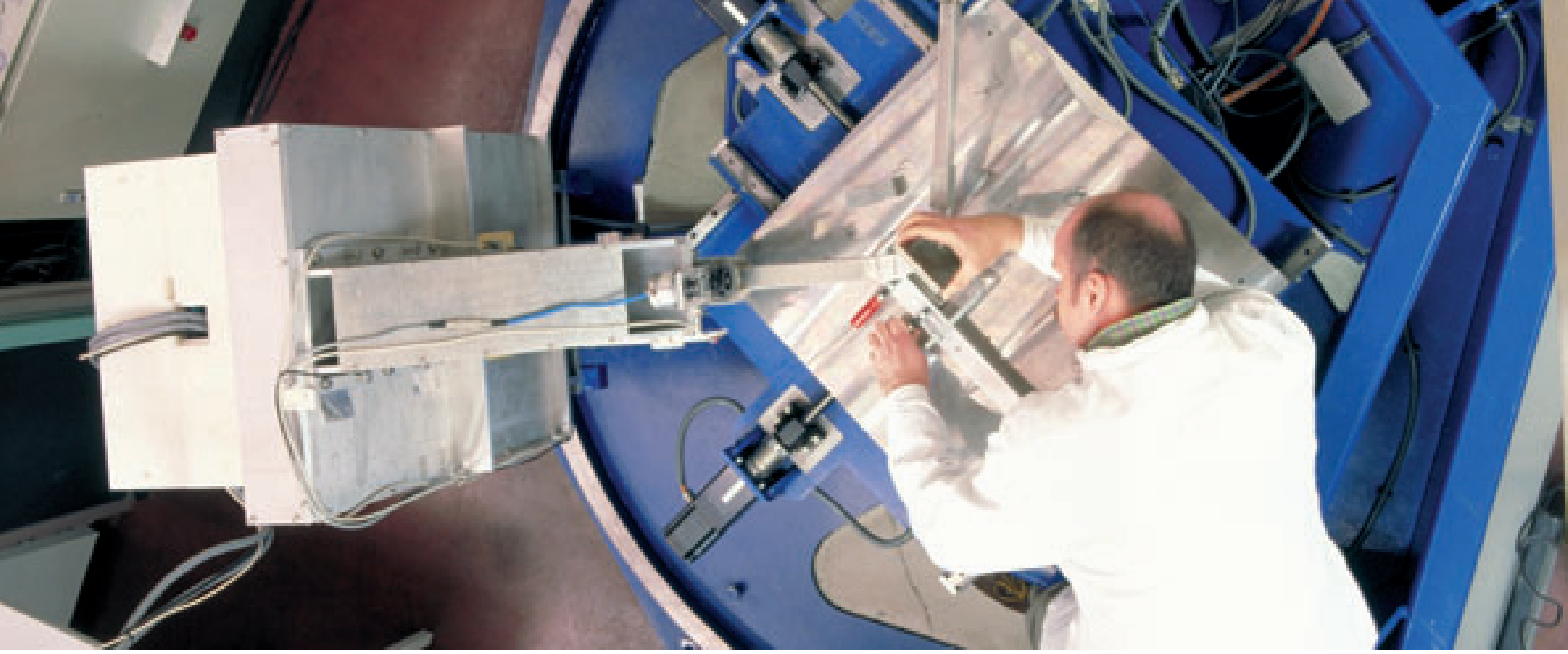
HIGH INTENSITY POSITRON BEAM (HIPOS) AT THE HFR - EXPLORATORY RESEARCH PROJECT

Progress of the JRC Exploratory research project (ERP) HIPOS has been achieved in 2006, mainly thanks to the scientific collaboration of JRC scientists and NRG nuclear engineers. This strong contribution exploited research potential of both institutes. Different sets of theoretical and experimental tasks at the HFR experimental beam line HB9 (Figure 21) were successfully accomplished, in particular:

- Validation of radiation transport calculations;
- Calculation of neutron and gamma flux;
- MCNPX and GEANT4 calculations of positron beam intensity.

An important milestone was achieved in calculating the positron yield using the computer code, MCNPX. The results confirmed that the integral intensity of the positron beam at the level 10^{13} positrons/sec can be reached (Figure 22). Such high intensity is required for fundamental reasons, in particular, to be able to collect an image of defects with better resolution, equivalent to the present generation of positron microscopes.

A parametric study for material optimization (Figure 23) and geometrical design of the positron generator was also carried out. Moreover, a benchmarking of two computer codes (MCNPX and GEANT4) was recently completed. A modular concept for future research reactors (Horowitz, Pallas) is under development. The finalization of the HIPOS project is planned for May 2007.



INNOVATIVE POWER CONVERSION CYCLES

With the objective to make high temperature process heat applications a reality in the short- and medium-term, conceptual design work was performed to investigate the feasibility and efficiency of a medium-temperature, CO_2-cooled reactor, based on modular HTR technology for combined electricity and high temperature process heat applications. A concept was proposed that is based on a primary cooling circuit with a maximum cycle temperature of 640°C, similar to a conventional British Advanced Gas Reactor.
A secondary reverse Brayton cycle acts as a heat pump by compressing gas up to the desired temperature level depending on the process heat application and on evolving material limits. The configuration is completed by a bottoming power conversion cycle that produces at least the electrical or mechanical power for the compressor in the heat pump.

Process Heat Applications
A process review was performed supporting in particular synthetic liquid hydrocarbons as optimum energy carriers for the future as opposed to hydrogen. These hydrocarbons can be produced by various carbon sources including smoke stack CO_2, water, hydrogen and process heat.
Several processes to produce synthetic hydrocarbons were looked at and compared, and methods were outlined as to how nuclear power in the form of electricity, process heat and hydrogen could help reduce CO_2 emissions or even act as a CO_2 sink.
An estimate was given about the requirements in terms of nuclear power and clean water to provide synthetic hydrocarbon fuel for a major European airport.
The involved organic chemistry processes are already largely used in today's chemical industry. They operate at temperatures that require process heat; the production of which is feasible with nuclear power. The market potential for combined nuclear-chemical plants is large, and massive savings in CO_2 emissions could be achieved.
From the available sources, it can be demonstrated that synthetic hydrocarbons could already today be produced at prices that are not only comparable with fossil fuel but also more stable, with no tax loss for the governments.

HFR as a Tool for Medical Applications

BORON NEUTRON CAPTURE THERAPY - BNCT

Background

The IE Action on the Development and Exploitation of Neutron Capture Therapy has made a number of significant steps during 2006, with work in a wide spectrum of activities around BNCT. Since the first demonstration of BNCT in Europe in October 1997 at the IE's High Flux Reactor (HFR), and the subsequent development and implementation of BNCT at a number of centres throughout Europe (Finland, Czech Republic, Sweden and Italy), the work at Petten is not only continuing to perform clinical trials, but it is also intensifying its research activities into dosimetry, treatment planning, radiobiology, boron compound testing and looking at other types of cancer, as well as non-cancerous diseases that could be candidates for BNCT. Furthermore, the know-how developed at Petten over the years is regularly in demand from other European research centres, as well as worldwide. In this context, the Petten BNCT group regularly organises seminars on different topics related to BNCT, co-organise workshops in other countries and provide consultation services as invited experts to interested groups.

Outside Europe, BNCT continues at two Japanese facilities (the JRR-4 reactor of JAERI and at the KUR reactor at Kyoto) and at the RA-6 reactor Bariloche (Argentina). BNCT projects are also in progress in many other countries, where facilities have been or are being constructed, such as in the UK, Taiwan, Italy, USA, Russia, South Korea and in many of the New Member States. All these groups were represented at the most recent biennial Congress on NCT, which was held in Takamatsu Japan in October 2006.

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.

The group itself was extended with the arrival during the year of another PhD student (Josselin Morand - jointly from Nice and Essen Universities) and a visiting professor in radiobiology (Andrzej Wojnik from Swietokrzyska Academy, Institute of Biology, Department of Radiobiology and Immunology at Kielce, Poland).

Clinical trials on BNCT at the IE - status

In previous Framework Programmes, three clinical trials on BNCT received support. These are:

- ***EORTC Protocol 11961: Post-operative treatment of glioblastoma with BNCT at the Petten Irradiation Facility: Phase I Clinical Trial***
  This trial was closed in 2004, following the treatment of the last patient in 2003. The final report on outcome, conclusions and recommendations is pending.

- ***EORTC Protocol 11001: ^{10}B-uptake in different tumours using the boron compounds BSH and BPA***
  This trial looks into the possible uptake of boron into different tumours, including thyroid cancer, head and neck cancer and liver metastases. If successful in terms of significant uptake of boron in the cancerous cells, patients with one of these types of tumour could become candidates for BNCT. Several more patients were entered into the study during 2006 at Essen University hospital. Tissue and blood samples taken from the patients in the operating theatre in Essen were sent to Petten for measurements by prompt gamma ray spectroscopy at beam tube HB7 to determine the amount of boron in the tissues. Results support the development of BNCT for the treatment of liver cancer.

- ***EORTC Protocol 11011: Early phase II study on BNCT in metastatic malignant melanoma using the boron carrier BPA***
  This trial has the objective to treat brain metastases of malignant melanoma using the boron compound, BPA. The trial was opened in 2004. During 2006, a patient was treated with up to 30 tumours in the brain. IE's role in the treatment is to perform the treatment planning using the code NCTPlan, to ensure that the facility is fully operational and functioning, and to coordinate all the technical aspects of the treatment, including security, technical reporting and availability of required staff. Due to the fact that these patients have multiple metastases throughout the brain, a very homogeneous irradiation dose distribution is essential. As such, patients receive five beams on

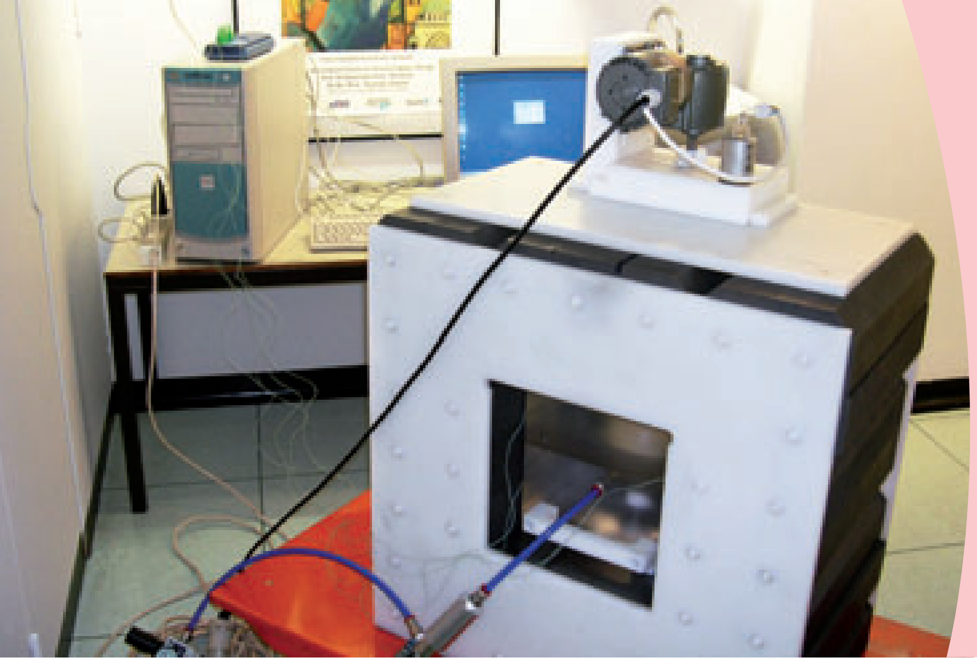


Figure 24 - Liver facility with Cold Gun Sprays® fitted

two consecutive days. Initial results showed that BNCT has a positive effect on all tumours, which is rarely seen for such patients. Due to this type of multi-beam, fractionated treatment, as advocated by the trial's principal clinical investigator, Prof. Dr. med. Wolfgang Sauerwein, over 200 BNCT procedures (beams) have been performed at the HFR. For a number of reasons, mainly because of no more support from the EORTC, due to economical and managerial changes, and due to fewer than expected such patients becoming available, only one patient was treated in 2006.

Application of BNCT to other types of cancer – Liver metastases

The application of BNCT to other cancers than brain cancer, supplements studies performed elsewhere in the BNCT community, where there is a need to demonstrate that BNCT is indeed a viable therapy for a variety of diseases. Notably in Japan, the application of BNCT is performed for many types of brain tumours, for melanoma metastases at many locations in the body, for head and neck, pancreatic, lung and liver cancer.

With respect to liver, liver metastases are the most frequent kind of malignancy in Western countries (Europe and North America) and represent the most frequent site of recurrence of any primary tumour. Survival of patients with liver metastases depends primarily from the stage of the primary tumour, nevertheless untreated patients invariably have a poor prognosis. Consequently, and due to the success demonstrated in 2001 by the group of Professor Aris Zonta and co-workers at Pavia Italy, who performed extra-corporeal treatment of liver metastases by BNCT, i.e. the liver is removed in the operating theatre, taken to the reactor for BNCT, and then returned to the hospital for re-implantation into the patient, studies are underway at Petten in collaboration with the University Hospital Essen to perform a similar treatment at the HFR. The project won additional funding from the JRC's Innovation Project scheme in 2005.

In 2005, a special facility was designed[1] and built at Petten to hold the liver during treatment. Unlike the Italian experience, where the liver was placed in the thermal column of the reactor, which effectively surrounds the liver by thermal neutrons only, the design at Petten had to develop a technique to perform the same treatment but using a directed beam of epithermal neutrons. A successful design was completed and was reported in 2005, when also some initial validation measurements were carried out. These tests were continued in 2006, with a test of the cooling of the facility (the liver will need to be kept at a temperature of approximately 4°C, for over two hours) and more sophisticated dosimetry measurements, using gel dosimetry, to validate the neutron and gamma conditions.

- ***Cooling tests***
  Cooling of the facility is provided by Cold Gun Sprays®, which are ingenious and simple devices that by means of the principle of a vortex tube, utilise standard compressed air to produce a jet of cold air at more or less zero degrees. Tests with the facility (see Figure 24) have shown that two cold sprays can maintain the facility at the required temperature for up to three hours.

- ***Gel dosimetry***
  In 2005, some initial measurements using activation foils and gel dosimetry were performed. The results were reasonably satisfactory. Nevertheless, more accurate measurements were required. As such, the gel dosimetry work was more rigorously repeated in 2006. This work was carried out in collaboration with the University of Milan, who are specialist in the field. Gel dosimetry is a technique to obtain continuous images of the absorbed dose. By properly designing the gel isotopic composition, it is possible to separate the gamma dose and the dose due to charged particles, such as those produced in ^{10}B reactions, and consequently the thermal neutron flux can be deduced. The method gives an excellent indication of the thermal neutron flux and the doses along pre-defined axes in the plane of the dosimeters, which were positioned in the liver holder and surrounded with water. Typical results are shown in Figure 25.

Application of BNCT to non-cancerous diseases – Rheumatoid Arthritis – project status

With respect to arthritis, 1-2% of the total population in Western countries develop a disorder that affects joints and/or their surrounding tissues, for example: rheumatoid arthritis (strong cartilage degradation) and osteoarthritis (both cartilage degradation and cartilage synthesis at undesired locations). This percentage is increasing nowadays due to

[1] V. A. Nievaart, R. L. Moss, J. L. Kloosterman, T. H. J. J. Van Der Hagen, H. Van Dam, A. Wittig, M. Malago, W. Sauerwein: Design of a rotating facility for extracorporal treatment of an explanted liver with disseminated metastases by boron neutron capture therapy with an epithermal neutron beam. Radiation Research 166, 81-88, 2006.

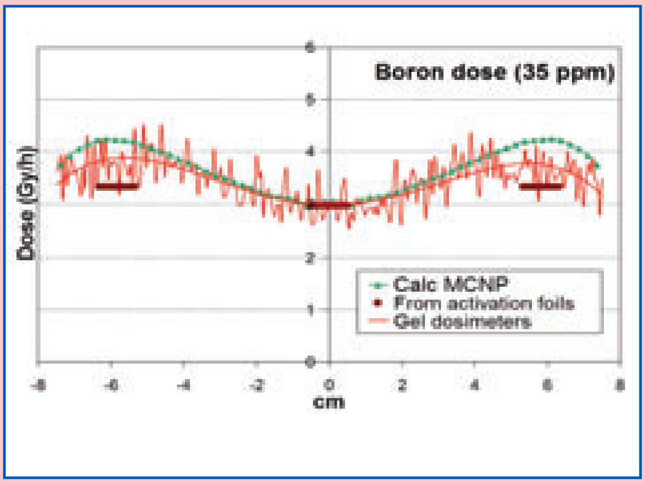


Figure 25 - Comparison between calculations and measurements using the gel dosimeter

ageing of the population. The synovium, a thin, weak layer of tissue only a few cells thick which lines the joint space and controls the joint fluid composition in normal situations, is most often the site of treatment in arthritic patients. In these patients, the synovium has turned into an aggressive tissue, invading cartilage and is highly infiltrated by immune cells. Macrophages appear to play a pivotal role in the function of this aggressive synovium, called pannus, because they are highly present in the inflamed synovial membrane and at the cartilage-pannus junction being clearly activated. Synovectomy, the removal or killing of this aggressive tissue in patients, is often performed and involves surgery, chemotherapy or radiotherapy and combinations thereof. However, this approach is seriously hampered by the safety aspects.

The macrophages play an important role in the severity of the inflammation process. They possess widespread pro-inflammatory, destructive and remodelling capabilities that can critically contribute to acute and chronic disease. Therefore, selective counteraction of macrophage activation is an efficacious and specific approach to diminish local and systemic inflammation, as well as to prevent irreversible joint damage. One possibility is BNCT. In collaboration with the Dutch universities of Delft and Nijmegen, high concentrations of the boron-10 can be achieved using liposomes, as the boron carrier. These small phospholipid-based vesicles can accommodate both hydrophilic and hydrophobic compounds and can easily be designed to achieve diseased site or even cell-type specific accumulation of ^{10}B compounds (BSH) after systemic or local administration. Activation of the compounds after appropriate incubation times is induced locally by irradiation of the inflamed joint with a thermal neutron beam.

The project received additional funding from the IE's Exploratory Research budget. Some initial probing irradiation experiments were performed in 2005, where cells indicated high boron uptake and mice with arthritic knee joints, indicated a reduction in size of the inflammatory joints and elimination of the synovial macrophages (see Figure 26). The next phase of the study is to demonstrate the idea through further experiments. It should be further noted that these approaches may not only be beneficial to the treatment of athritis but also to other types of (autoimmune) inflammatory disorders. Due to delayed contractual procedures, no experiments were performed in 2006. Nevertheless, the project did result in a number of publications. The experimental programme will re-start in 2007.

JRC Institutional Programme on BNCT

The research and development activities of BNCT at Petten are supported in the JRC's Institutional Research programme. The studies into the applicability of BNCT to other types of cancers and non-cancerous diseases are reported above.

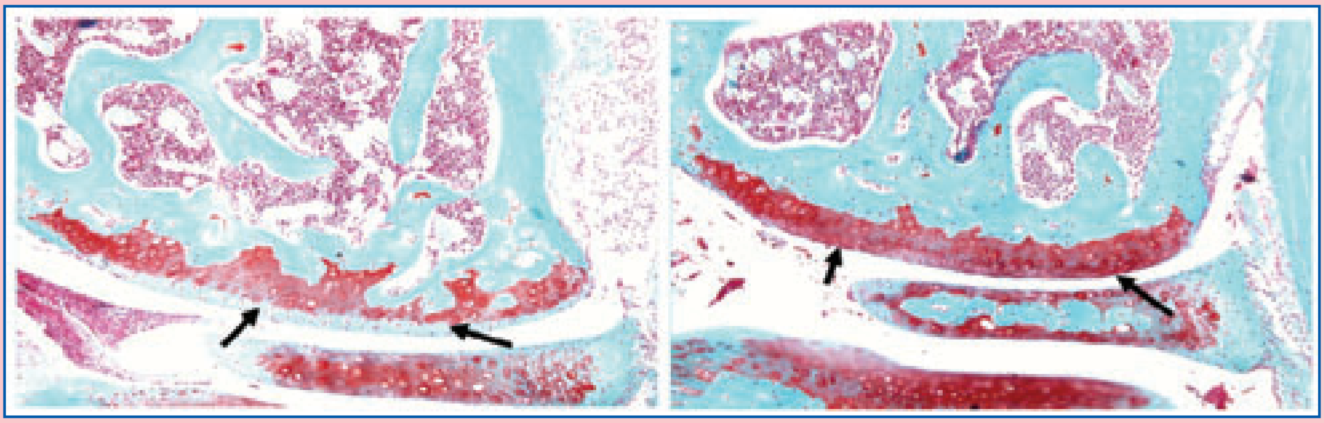


Figure 26 - Selective elimination of synovial macrophages prior to induction of experimental arthritis prevents early cartilage destruction

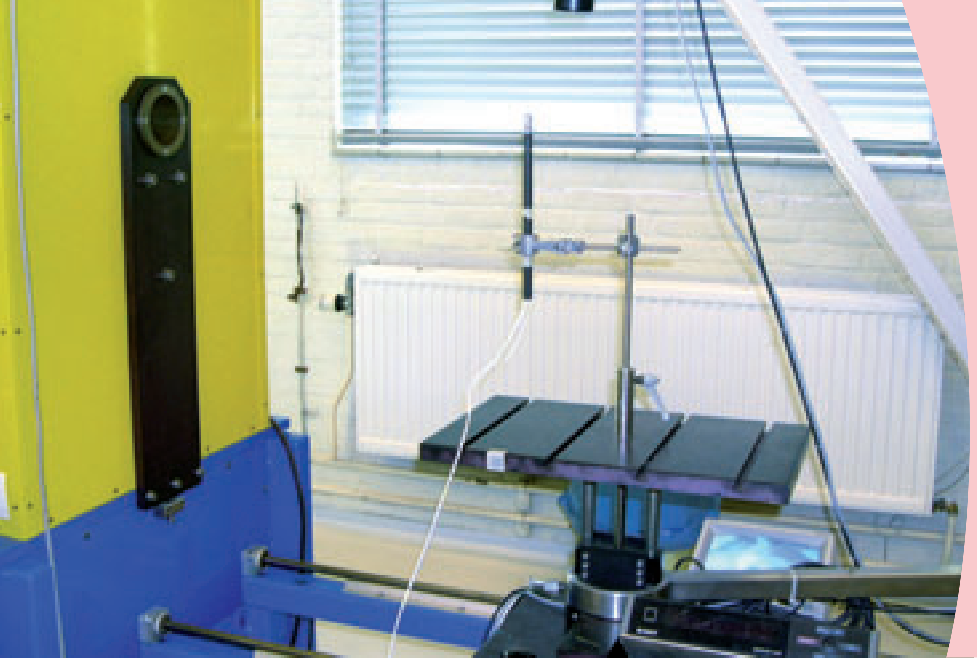


Figure 27 - Exposure of an ionisation chamber at the Cobalt-60 source in the LFR building (NRG Petten)

Other topics, such as treatment planning[2,3] and improvement of the BNCT facility are continuous actions that have been reported over the years. Another topic is dosimetry, i.e. through measurements and calculations, knowledge of the radiation characteristics of the incident neutron/gamma beam and the absorbed dose in tissue, as a result of the irradiation of the patient.

Beam dosimetry

A campaign of measurements using the so-called paired ionisation technique, principally using TE(TE) and Mg(Ar) chambers, is the subject of one of the BNCT Group's Ph.D. students (Neta Roca). The technique is standard daily practice in conventional radiotherapy departments. As such, it is recommended for use in BNCT. However, due to the nature of a BNCT radiation beam, which is a mix of neutrons and gammas, the paired ionisation technique is often only applicable, when applied at a fixed position.

Furthermore, correction factors to convert the measured signal to dose are subject to high variability and inaccuracies. The measurements performed at the BNCT facility, aim to obtain a comprehensive understanding of the technique, when applied at any position in the beam, whether in a phantom or not. The work involves modelling the chambers in detail using the reactor physics code MCNPX. The first part of the study compares the results from photon-only (^{60}Co) measurements (see Figure 27), which were completed in 2006. The work in 2007 will extend this to photon/neutron fields and then in tissue (phantoms). The computational model determines the charge created in the ionisation chamber due to the released electrons, which has not been done before.

As part of this study, and also as part of the group's activities to encourage collaboration, Prof. Rainer Schmidt (Hamburg University) and two PhD students visited Petten to perform measurements with their own ionisation chambers, which complemented the work of Neta Roca.

Radiobiological Dosimetry

The physical dosimetry measurements can be validated by methods of biological dosimetry. This technique relies on estimating the level of chromosomal aberrations in human peripheral blood lymphocytes (PBL) exposed to radiation. Although no absolute doses can be derived from the results, the shape of the dose response curve can be regarded as a method of dose validation. PBL of two donors were irradiated with different doses of neutrons in the HB11 beam, calculated by MCNPX. Preliminary results are shown in Figure 28. As expected, a linear dose response curve was observed, confirming that the MCNPX calculations are correct.

Treatment Planning

The trial on multiple brain metastases due to malignant melanoma, as reported above, may involve up to 20 or more metastases in the brain, as well as taking into account the organs at risk (OARs) and the regions of interest. A multi-beam treatment concept is mandatory. Applying neutrons in BNCT requires complex treatment planning using non-commercial codes, which have been developed based on Monte Carlo calculational tools. Such a multi-beam plan may require numerous, e.g. up to 10 or more separate beam calculations (see Figure 29). A combination of three or more beams finds an optimal dose distribution. Until now these calculations have been very time-consuming, sometimes taking 4-5 days. In order to accelerate this procedure, linear programming techniques have been applied, which take into account all calculated beams, all tolerance doses of each organ at risk and other parameters, if necessary.

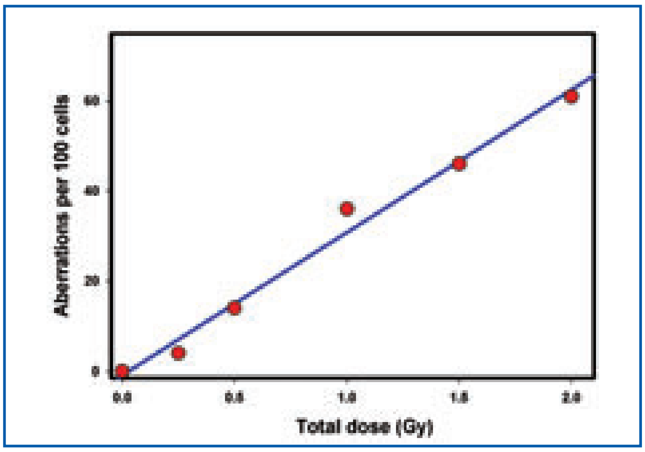


Figure 28 - Plot of Chromosonal Aberrations versus dose

(2) Cerullo N., Daquino G.G., Bufalino D. - PET and MRI based treatment planning systems: a methodology for a realistic evaluation of the dose and fluence distributions in BNCT and in GdNCT - Jour. Phys. Conference Series 41, pp. 203-211, 2006

(3) Cerullo N., Daquino G.G., Muzi L. - An overview on the developments and improvements of a treatment planning system for BNCT - Trans. Nucl. Science, Vol.53, issue 3, pp. 1333-1338, 2006

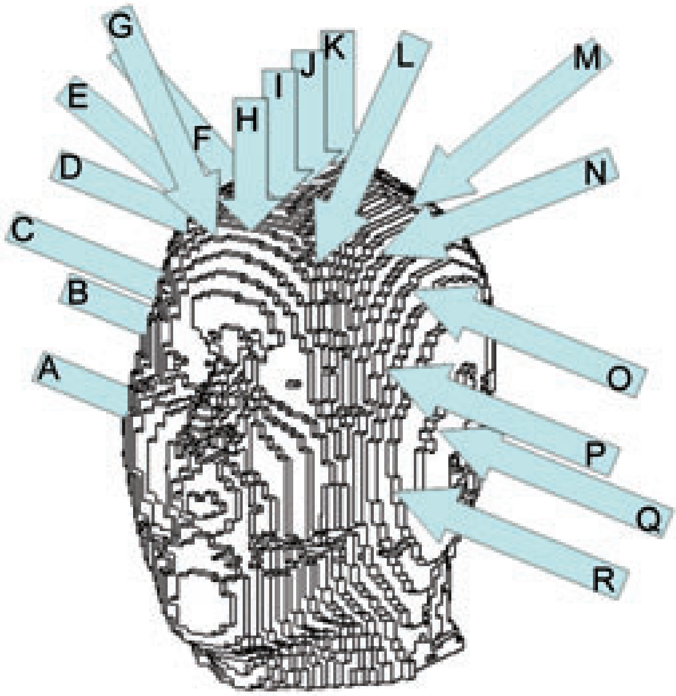


Figure 29 - Possible beam directions (to head model) requiring for each, a separate calculation

The Simplex method is a method for solving problems in linear programming. This method, invented by G. Dantzig, tests adjacent vertices of the feasible set (which is a polytope-like point, line segment, polygon, polyhedron, ...) in sequence, that at each new vertex the objective function improves or is unchanged. The Simplex method is very efficient in practice and converges in expected polynomial time for certain distributions of random inputs [from mathworld.wolfram.com]. The resulting calculation produces more quickly than before, a unique optimised plan. More importantly, this treatment plan shows a reduction of the overall irradiation time by up to 30% (cf: manually obtained treatment plans), thus reducing doses significantly to healthy tissues. Such a procedure may also be of interest in conventional radiotherapy.

MISSIONS, SYMPOSIA AND VISITORS

Numerous meetings were attended to discuss progress and collaborative actions, as well as organising and/or attending conferences and symposia. These included:

12th International Congress on Neutron Capture Therapy, Takamatsu, Japan

The biennial congress on Neutron Capture Therapy was this year held in Japan. There were 211 participants from 21 countries. Special award sessions included the Fairchild Award, which honours young scientists in the field of BNCT, who have produced some excellent publications. Sander Nievaart received one of the awards[4].

The Congress was arranged into three special lectures, 23 oral sessions (nine plenary sessions – 44 papers, 14 parallel sessions – 70 papers) and two poster sessions (79 posters). In addition, special meetings of the Executive Board and Board of Councillors were held, of which Ray Moss is the secretary/treasurer.

Presentations at the meeting included recent work on mainly brain tumour studies in Japan and Europe, but also treatments of other cancers, such as, Head and Neck, recurrent glioblastoma, multinodular skin melanoma, Cutaneous and Mucosal melanoma, combined photon + BNCT studies (with very good outcome), liver cancer and thyroid cancer.

"Balkan Medicine towards FP7", Bucharest, Romania

This 3-day event was organised by the Romanian Ministries of Education and Research (MER) and Health (MH), the National Authority for Scientific Research and the European Commission. BNCT was one of the many medical topics discussed, where possible collaborative actions could be envisaged. Furthermore, a separate meeting had been arranged between representatives from the Ministry of Research and with the president of the Romanian Nuclear Agency to discuss the Joint Undertaking/HFR/Romania.

Day 2 included a special workshop on "Biomedical Research driven by Balkan's SMEs in re-launching the Lisbon Strategy". R. Moss presented the BNCT programme, with particular emphasis on JRC's Enlargement and Integration Action.

---

(4) Victor Nievaart: "An optimum source neutron spectrum and holder shape for extra-corporeal treatment of liver cancer by BNCT", Ralph G. Fairchild Award of the International Society for Neutron Capture Therapy, 12th International Congress on Neutron Capture Therapy, Takamatsu, Kagawa, Japan, October 2006

During the 3-day period, a visit was also arranged to the Institute of Oncology, at the "Prof.Dr. Alexandru Treistioreanu" Hospital Bucharest, where the clinical part of a potential Romanian BNCT project is run. There was particular interest in liver cancer.

JRC Information Day, Bucharest, Romania
This event, organised between the JRC Brussels and the Romanian Ministry of Education and Research, included a presentation by Neta Roca (Romanian PhD student in the BNCT Group in Petten) on BNCT.

Fast Neutron Therapy Workshop, Essen
Fast neutron therapy is closely related to BNCT, with radiotherapy centres in Europe, USA and South Africa. This workshop, organised by University Hospital Essen, included a strong participation by the Petten BNCT group, with three presentations and four posters presented by the Petten group.

Innovation Project Meeting, Ispra
The liver project is partly funded by the JRC's Innovation Project, following a successful application in 2005. This meeting brought together all project leaders, similarly funded within the JRC. The IE Liver project was one of eight presentations.

Visit to IE Petten of Russian delegation
A strong delegation of six scientists and clinicians from Moscow (various institutes, including the University of Moscow) visited Petten to learn of the BNCT activities here and to discuss potential collaboration. Each project was presented from both sides. The Russians had made some surprisingly advanced studies already some 10 years ago in BNCT, including extra-corporeal treatment of bone cancer in dogs.

EDUCATIONAL AND DISSEMINATION ACTIVITIES

Seminars in 2006, held at IE Petten
With a growing team of students, post-docs and visiting scientists to the IE BNCT group, there has been a concerted effect to create an educational programme for the group and any interested staff in Petten. The invited speakers covered a wide variety of topics related to the disciplines of BNCT. The (almost) monthly programme for 2006 was:

Month	Name	Institute	Title of Talk/Presentation
Jan	Dr. M. Tenhunnen	Helsinki University Hospital, Finland	Radiotherapy: Role and Duties of a Medical Physicist
Feb	Dr. Gerard Krijger	Technical University of Delft, The Netherlands	Development of Drugs for BNCT
Mar	Prof. Stephan Grabbe	University of Essen, Germany	Malignant Melanoma
Apr	Prof. Rainer Schmidt	University of Hamburg, Germany	Neutron Dosimetry
May	Prof. John Hopewell	Oxford University, UK	The Radiobiology of High LET radiation and its application to BNCT
Jun	Dr. Stuart Green	University Hospital Birmingham, UK	Medical Physics: Treatment Planning for Binary Radiotherapy
	Prof. Kent J. Riley	MIT, USA	Int. Dosimetry Exchange on Epithermal Neutron Sources for BNCT
Jul	Prof. Jan Heimans	VU medical center Amsterdam	Neuro-Oncology
Aug	Prof. Massimo Malago	University Hospital Essen, Germany	Liver Transplantation
Sep	Prof. Vincent Grégoire	Université Louvain-la-Neuve, Brussels	Achievements in Radiotherapy
Nov	Dr. Albert Keverling Buisman	Nederlandse Vereniging voor Stralingshygiëne	Radiation Protection Aspects of BNCT
Dec	Prof. Guy Storme	AZ-VUB, Bruxelles	1. Organisation of European Cancer Institutes and its Working Group on New Technologies 2. Image Guided Radiotherapy in daily practice

A similar effect is envisaged in 2007.

E&I Liver Workshop Essen

As part of the JRC's Enlargement and Integration Action (EIA), a workshop was organised to bring together interested groups to discuss whether it is worth to intensify efforts to use BNCT for the extra-corporeal treatment of liver cancer. The concept was used in Pavia 5 years ago to cure multiple liver metastases in two patients. This observation motivated a number of colleagues to investigate this topic. The emphasis of the workshop was on the medical side, as there is a need to discuss with the specialists in the field on the necessity of such a complex treatment. The specialist physics and radiobiological aspects were also discussed.

The workshop took place in Essen and was co-organised by the University Duisburg-Essen and the IE. The workshop took place at the University Hospital. It was organized in a way to allow as much discussion as possible. The programme included many topics related to the treatment of liver cancer and diseases in general. The topics were presented by specialists in the field. It was the first time that such a large number of specialists in the treatment of liver cancer were brought together. Topics presented included:

- Functional organisation of liver tissues and pathways for tumour metastasis;
- Acute and Chronic liver diseases;
- Current therapeutic options for primary liver tumours;
- Efficacy of BNCT in liver metastases in a rat model;
- Towards a new therapy protocol for liver metastases: effect of boron compounds and BNCT on normal liver regeneration;
- Treatment of liver metastases by drugs;
- Radiotherapy in multiple liver metastases;
- Surgery for liver metastases;
- Surgeons perspective on liver transplantation;
- Boron uptake in liver - Results from EORTC trial 11001;
- Boron concentration measurements in liver metastases;
- Extracorporeal liver irradiation in the thermal column of the Pavia Triga reactor;
- Is extracorporeal liver cancer treatment possible in an epithermal neutron beam;
- Validation studies for the Liver treatment facility in Petten.

The conclusion of the meeting was that BNCT could offer a complementary therapy for liver cancer and as such, research in this area should continue.

MISCELLANEOUS

BNCT Radiation Protection Committee

The licence conditions for BNCT at the HFR Petten require that a special committee on Radiation Protection should exist. The Committee, which was set up in 1997, has met regularly throughout this period. All the disciplines associated with BNCT are represented on the Committee. No contentious issues had been raised throughout the year, indicating that the radioprotection aspects of BNCT at Petten are well respected.

BNCT Review

After more than 10 years of BNCT activities at IE Petten, it had been requested by JRC HQ, that a review of BNCT in Petten should take place. The review panel consisted of four independent experts in related fields, but who were not directly involved in BNCT. The strategy for BNCT for the coming years was amongst the issues reviewed, as well as the plans to maintain an underlying stability regarding staffing and the budget. Mainlines reviewed were:

- The scientific excellence of the research performed;
- The project's high profile in the BNCT and medical community;
- The training offered to (young) scientists: PhD students, visiting scientists, seminars.

It is planned that the review report will be presented to the Director General, in early 2007.

MEDICAL RADIOISOTOPE PRODUCTION

The year 2006 was a challenging year for the production of medical isotopes. The period saw the important completion of the nuclear non-proliferation conversion from High Enriched Uranium (HEU) to Low Enriched Uranium (LEU) fuel. This conversion process had consequences for the production capacity for some of the isotopes produced in the HFR.

The HEU-LEU fuel conversion has now been completed successfully and an equilibrium core with LEU fuel has been reached. This was a difficult period for planning and scheduling of the production of isotopes and HFR appreciated the high level of support that it received from customers during the conversion period. NRG staff was able to maintain the HFR's overall performance at a high level during the conversion period, with only a limited overall disruption to supply.

Following the HEU-LEU conversion, the HFR is now operating with a different cycle schedule with significantly longer irradiation cycles; approximately more than 15 percent of additional irradiation time per cycle. This adjustment also results in fewer irradiation cycles, but retains the same total irradiation time and reduces the number of short-duration supply interruptions per year. The new operating schedule required some changes to working practice; but overall, has provided a positive benefit for the availability of medical isotopes.

The year also saw unusually large variations in the demand for some isotopes due to a number of unscheduled disruptions to the production capabilities of some customers, as well as the supply capability of competitors. The result of this led to some periods of reduced production levels at the HFR, but also led to some significant periods of record high levels of production. The final closure in May 2006 of the FRJ-2 reactor at Jülich in Germany, also added to the total workload demand at the HFR.

Important medical isotopes continued to be molybdenum-99, iridium-192, strontium-89 and iodine-125, but medical therapy isotopes such as samarium-153, phosphorus-32 and lutetium-177 grew in their importance. Overall the supply of all isotopes grew by more than five percent during 2006 and the supply of medical isotopes grew by more than 10 percent. The total supply of medical isotopes rose to a new record level in 2006.

Programmes supporting the development of various new medical research initiatives continued strongly in 2006, with an increase in demand for these services. The availability of suitable production facilities that can be reloaded with target materials while the HFR is 'on-power' continued to be important in the support of developing and early stage clinical trial work.

The continuing growth in demand for irradiation services from the HFR has led to the development of a number of technical programmes for 2007 aimed at improving the efficiency of utilisation and increasing the overall irradiation capacity of the HFR. These programmes will help to ensure that increasing demands can be met effectively.

The HFR is well positioned for continued strong and reliable performance to provide the vital medical isotopes demanded by modern medicine.

HFR as a Tool for Fission Reactor Technology

HIGH TEMPERATURE REACTOR FUEL IRRADIATIONS IN THE HFR

Background

The HTR is a helium-cooled, graphite moderated nuclear reactor. The high temperature coolant output, effective fuel use, large amount of R&D experience and inherent safety make it a very economically viable 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 in a porous graphite buffer layer and a pyrocarbon-silicium carbide-pyrocarbon coating. 10,000-14,000 of these particles are contained in a graphite matrix in the form of a sphere or pebble of diameter 6 cm (Figure 30)

Two irradiation tests of Low Enriched Uranium fuel types were carried out in the HFR, with further preparations 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).

Work performed in 2006 was marked by three events:

- Start of the Post-Irradiation Examination (PIE) of fuel pebbles irradiated in 2004-2005 in the HFR-EU1bis irradiation (1250°C central temperature, > 15% burn-up on five German fuels);
- further preparation and start-up of the HFR-EU1 irradiation (1200°C central temperature, 20% burn-up on three German fuels, 17% burn-up on two Chinese fuels);
- completion of a feasibility study for weak irradiation in one of the HFR neutron beams.

HFR-EU1bis PIE

The HFR-EU1bis experiment comprised of five HTR fuel pebbles, which were irradiated in the HFR core position G3, to investigate the capability of classical German HTR fuel to operate at conditions representative for the Generation IV International Forum VHTR reactor concept. An X-ray picture, taken in JRC's X-ray laboratory of the HFR-EU1bis capsule prior to irradiation is shown in figure 32.

After irradiation and cooling the irradiated fuel was transferred to the NRG hot cell laboratory. Four of the five pebbles were shipped to JRC-ITU for safety relevant heating tests in the KÜFA facility. In Petten, one pebble was prepared for destructive examination, as shown in figure 31.

Samples were examined using ceramography, electron probe micro analysis (EPMA) and ion etching, as well as hardness measurements of coatings and kernel. An example of a detailed ceramography of a single TRISO-particle at the periphery of the fuel pebble is shown in figure 33.

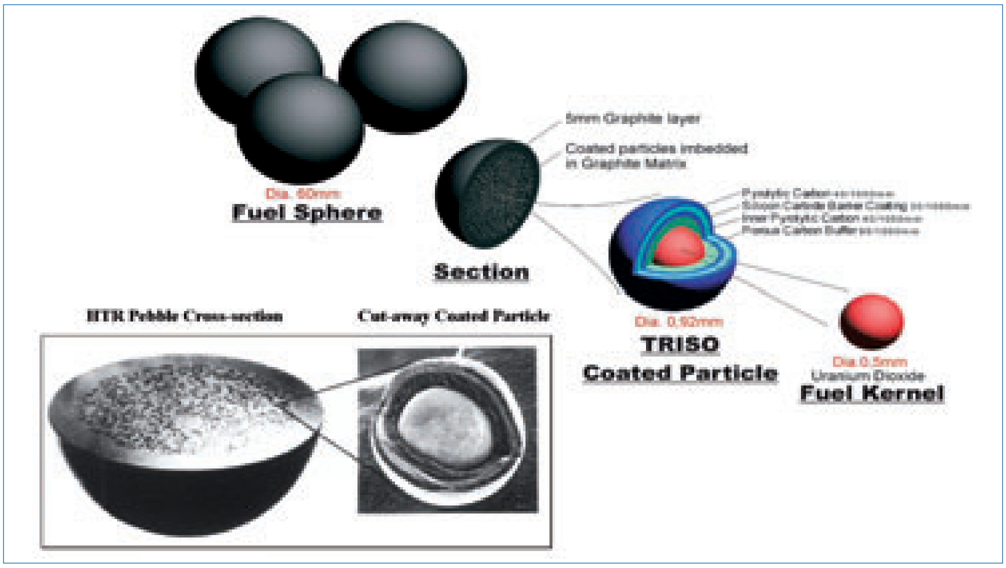


Figure 30 - HTR fuel sphere and pebble

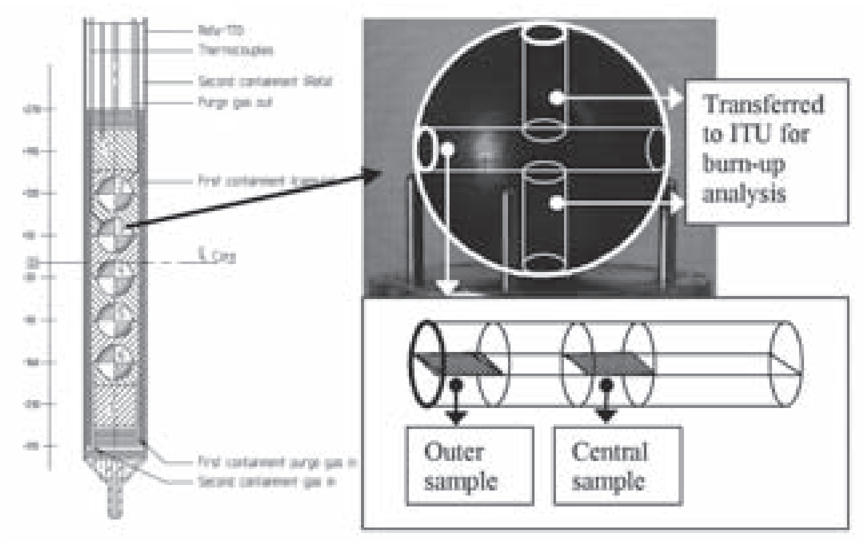


Figure 31

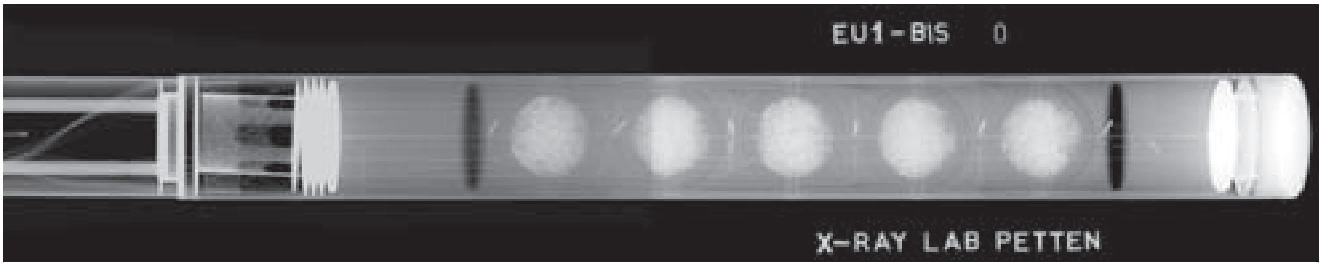


Figure 32

The PIE work has already yielded results that are of major influence on the applicability of existing HTR fuel fabrication technology at high temperatures and high burn-up. Additionally, a number of innovative post-irradiation techniques for irradiated HTR fuel were developed. The results will be shared with the European FP5 and FP6 projects HTR-F1 and RAPHAEL and will ultimately contribute to the related Generation IV International Forum Project.

Start-up of HFR-EU1

A new HTR fuel irradiation to very high burn-up (HFR-EU1) started in September 2006, with a planned duration of approx. 2½ years. A further such irradiation test (HFR-PBMRF1) is planned for start-up towards the beginning of 2008. Pre- and post-irradiation examinations will be conducted to test the safety relevant quality and temperature limits of the irradiated fuel. The results of these experiments are expected to provide orientations for further improvement of fuel technology. The irradiations currently in core or under preparation include:

- Irradiation of pebble type fuel produced by NUKEM Germany and by INET China, codename *HFR-EU1* with on-line fission gas release monitoring with respective target burn-ups of 20% FIMA for NUKEM pebbles and 17% FIMA for INET pebbles;
- Irradiation of pebble type fuel, newly produced by NECSA South Africa for PBMR, codename *HFR-PBMRF1* with on-line fission gas release monitoring. Target burn-up 11.5% FIMA.

The irradiation HFR-EU1 has been running smoothly since September 2006, with further improvement of on-line fission gas analysis being prepared for 2007. Before start-up, the new Sweep Loop Facility for automatic temperature control and on-line fission gas analysis was hot commissioned.
The collaboration agreement with INET China was extended for another five years.
In the framework of cooperation with the GIF project "VHTR Fuel and Fuel Cycle", a collaboration agreement with PBMR of South Africa was finalized. Nuclear and thermal calculations were performed, the design was optimized and contracts for fabrication and assembly were placed. Delivery of the fuel is expected in late 2007, enabling start-up of the irradiation in the beginning of 2008.

Weak Irradiation

A feasibility study was conducted in the framework of the FP6 RAPHAEL Integrated Project to evaluate weak irradiation testing of HTR fuel in the HFR neutron beam HB8, as an additional fuel qualification method to test the integrity of

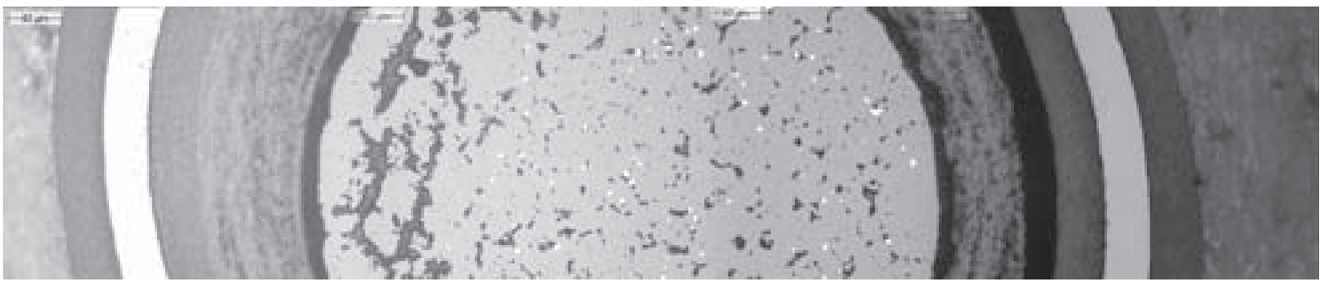


Figure 33

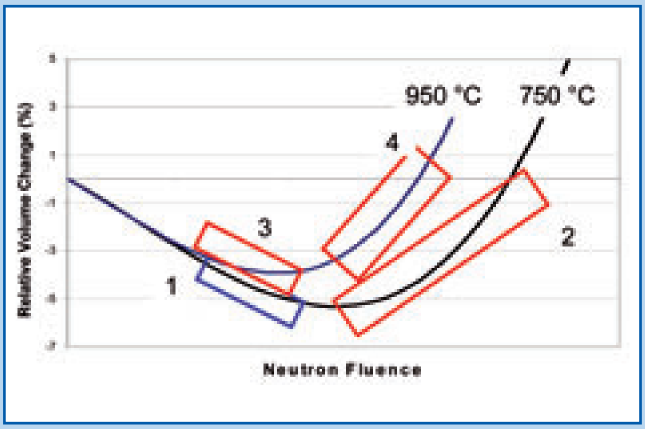


Figure 34 - Dose and temperature range for graphite irradiations in FP5 and FP6

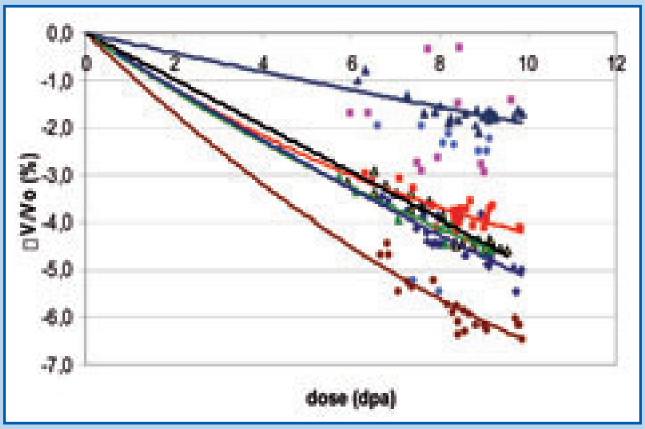


Figure 35 - Volumetric shrinkage behaviour of present day graphites irradiated in INNOGRAPH-1A at 750°C to 8 dpa_g

fresh fuel prior to long-term in-core irradiation. A conceptual design for such an installation was prepared. Neutron metrology in combination with neutronics calculations determined the locally achievable thermal neutron flux in the newly configured HFR core with LEU fuel. With these neutron fluxes as input, the required exposure times to detect characteristic fission gas R/B fractions (release over birth) of 10^{-5} from ^{135}Xe were estimated to be relatively long, i.e. 16 days for a single HTR fuel pebble. Although sensitivities of R/B = 10^{-8} are reported in literature, the achievable sensitivity in HB8 would mean that it is possible to detect a single leaking particle in a pebble from which 10% of the fission gas production is escaping.

Outlook

The renewed interest since the late 1990's in HTR technology has triggered major hardware and manpower investments into HTR fuel irradiation capability at the HFR. Consequently, in the period 2004-2010, on average, at least one HTR fuel irradiation test will be running in the HFR.
With the HFR Petten and the KÜFA facility at JRC-ITU, JRC is currently the only organization worldwide that can offer the complete fuel qualification chain, including irradiation, PIE and safety relevant heating tests. Innovative PIE techniques in the NRG hot cell laboratory in Petten is a useful completion of this spectrum.

STRUCTURAL MATERIAL OUT-OF-PILE TESTS FOR INNOVATIVE REACTORS

Background

Out-of-pile mechanical testing provides reference properties of high-temperature materials to be used in innovative reactors, e.g. as pressure vessel material, control rods or ancillary components. Later, specimens of candidate materials may be irradiated at conditions typical for their envisaged use. Post-irradiation testing will focus on determining possible irradiation-induced degradation of mechanical properties.

Achievements in 2006

Materials performance and possible strength deterioration due to hot gas corrosion by impurities in the primary He coolant are of concern in the design of HTR turbine components working in the direct cycle. To establish upper bounds for the mechanical properties degradation that can be expected, IN792 DS and CM247 LC DS blade materials were pre-exposed to different chemical environments leading to different material states, namely (i) ageing heat treated, (ii) fully decarburised, and (iii) heavily carburised. Afterwards the materials were creep tested at 850°C.
As a candidate disc material, the creep and the low-cycle fatigue performances of Udimet720 have also been studied at 750°C and at 650°C respectively, following pre-exposures resulting in a heavily carburised and in a fully decarburised state. In all cases, strength properties were observed to deteriorate by the corrosive pre-treatments as compared to the as-received materials. Optical microscopy, SEM and TEM investigations were carried out to characterise failure modes associated with the corrosive attack, as well as the creep and LCF damage.
For indirect cycle power conversion components (turbine, heat exchangers) exposed to a mixture of 80% N_2 and 20% He, the need to perform nitriding tests was identified and, consequently, work on that issue started in 2006.
For SCWRs, the assessment of the materials performance of ferrous alloys in supercritical water (SCW) is of major concern for the selection of structural materials. While experience from operating LWRs and supercritical fossil plants is available, the understanding of the behaviour of candidate materials in SCW with normal or hydrogen water chemistry is still insufficient in terms of the general corrosion and stress-corrosion cracking (SCC), as well as the irradiation-assisted stress-corrosion cracking (IASCC) susceptibility.
To contribute to the understanding of the basic corrosion kinetics, the monitoring of SCC by means of the acoustic emission (AE) technique has proven a sensitive in-situ corrosion monitoring technique. This has been shown using internally pressurized tubular specimens heated to SCW conditions and subjected to slow load-unload tensile tests. Moreover, a recently commissioned re-circulating water loop with autoclave designed for corrosion and SCC tests under SCW conditions has been used for slow strain-rate tensile testing of stainless steels at temperatures up to 600°C and pressures up to 360 bar. Future work will address fundamental issues of SCW stress corrosion kinetics as applied to candidate materials of interest to SCWR applications, e.g. ODS steels, the performance of which is to be compared to that of various Fe- and Ni-based materials investigated in FP6.

HTR CORE STRUCTURES GRAPHITES

Objectives

Extensive irradiation test programmes were performed more than a decade ago for earlier HTR projects. Today none of these earlier qualified graphites is produced com-

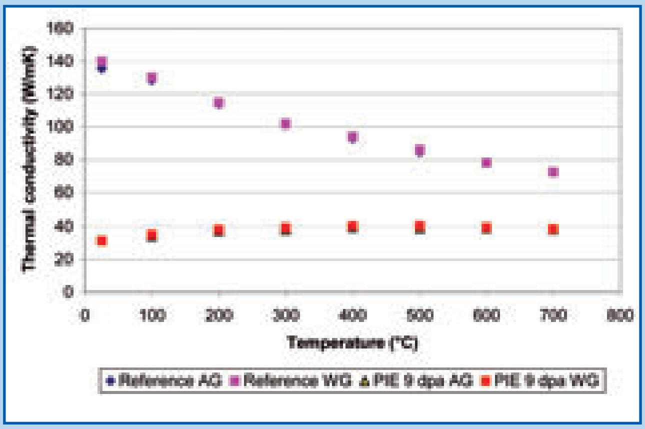


Figure 36 - The coefficient of thermal conductivity as a function of temperature of a typical extruded graphite, before and after irradiation to 9 dpa_g at 750°C. (It is assumed the specific heat of graphite is not changed during irradiation)

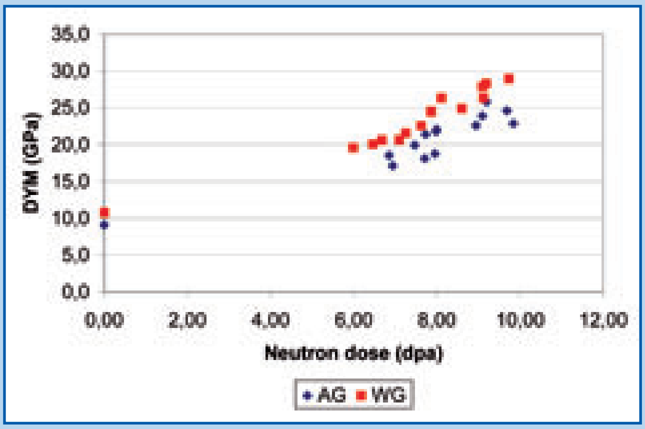


Figure 37 - The Dynamic Young's Modulus (DYM) of a typical isomoulded graphite, before and after irradiation to 9 dpa_g at 750°C. (It is assumed that the specific heat of graphite is not changed during irradiation)

mercially anymore, and most post-irradiation test facilities have become outdated. This has required the re-installation of qualification tools for HTR core structures graphite. This programme was started in 2002 by NRG within the HTR-M1 project and expanded into the RAPHAEL project from 2005 onwards.

Achievements in 2006

In 2006, post-irradiation examinations were performed by NRG for the INNOGRAPH-1A experiment, which had achieved a nominal dose of over 8 dpa (graphite) at a nominal temperature of 750°C. The rig contained 200 specimens from 8 different grades of potential candidates for a future HTR. The post irradiation examinations comprised of measurements of dimensional change, Young's modulus, thermal diffusivity and thermal expansion.

The current programme formed the basis for enlarging the test matrix within the follow-up project: RAPHAEL IP. A second high temperature rig, INNOGRAPH-2A, has been designed and assembled for irradiation at 900-950°C, which is at the high end of the (V)HTR window. This rig contains about 150 specimens and contains newer grades of graphite that became available in 2005. Irradiation in the HFR started June 2006 with a peak target dose of 6 dpa.

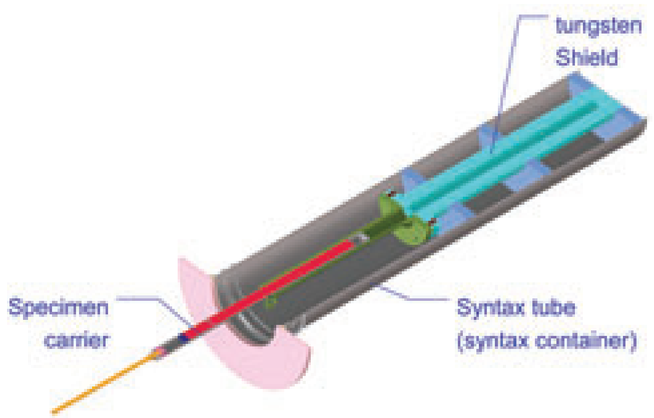


Figure 38 - Transport module for rigs loaded with low activity samples

A major part of the samples in INNOGRAPH-1A has been re-loaded to continue irradiation up to a 3 times larger dose in INNOGRAPH-1B, which will to start in early 2007. In 2006, 150 specimens were transferred to one of the HCL lead shielded facilities, where the final assembly processes are to bee performed which includes welding of the primary containment tube. A dedicated transport module has been developed and manufactured that will serve to transport the rig from the HCL to the HFR in early 2007.

During 2006, the activity was further aligned within the framework of the GIF VHTR project arrangements.

IRRADIATION OF HTR VESSEL MATERIAL AND POST-IRRADIATION TESTS

Objectives

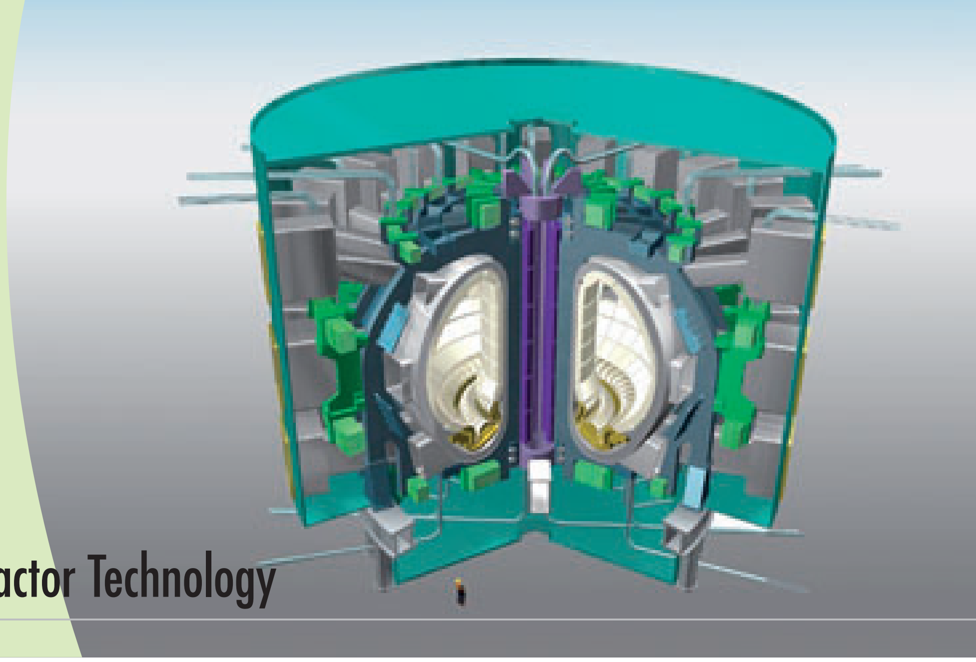
One of the alternatives considered for HTR is the application of the so-called hot-vessel. Modified 9Cr-steel could potentially be used up to 450°C. Thick-section weldments have been produced by Framatome ANP for reference, irradiation and post-irradiation testing of weldment and base metal.

Achievements in 2006

The irradiation of specimens cut from a T91 weldment was performed in 2005. Longer term post-irradiation creep tests for the FP6 RAPHAEL programme continued. The tests are performed with target rupture times in the range of 10^3 to 10^4 hrs.

FUEL IRRADIATIONS FOR THE IMPROVEMENT OF FUEL CYCLE ECONOMY

In the field of more specifically LWR fuel and cladding tests, the HFR is very suitable for the following irradiations:
Ramp testing of LWR fuel rods: the old facility is no longer up to the current technical standards. NRG is currently studying the option to upgrade the ramp test installation in order to be able to restart this type of test. The ramp tests were performed in the so-called Boiling Water Fuel Capsule (BWFC) facility, in which the conditions (PWR or BWR) can be achieved by external helium pressurisation of the capsule, in combination with sub-cooled boiling inside the capsule.



HFR as a Tool for Fusion Reactor Technology

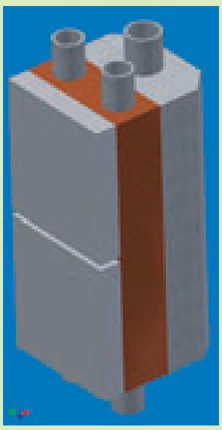
The signature of the agreement to implement the ITER fusion energy project on November 21 constitutes a fundamental milestone in the development of fusion energy.
HFR's high versatility provides extremely relevant R&D capabilities for fusion power plant technology. The HFR contributes to the fusion technology 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 blanket development and the development of the reduced activation materials: chromium steel and ceramic composites.

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 previously investigated the stress relaxation behaviour under neutron irradiation of two candidate materials Alloy 625+ and PH13-8Mo. A new irradiation campaign has been started to measure the irradiation response of PH13-8Mo materials in terms of yield stress hardening, elastic fatigue resistance and fatigue crack propagation up to 2 dpa. The irradiation capsule is a SUMO type, modified to have two temperature zones at 200 and 300°C.
NRG continued to assist the ITER Central Team in preparing the ITER Materials Properties Handbook (MPH). This includes reviewing and assessing irradiation effects on fracture mechanics properties of ITER grade 316L(N) stainless steel.
A new test facility for ITER primary wall modules is under construction, which will allow close simulation of thermal fatigue and simultaneously neutron loading in the HFR pool side. NRG is also developing with TNO alternative manufacturing routes for thick tungsten claddings on steel and on copper-base substrates.

Sub-modules for the Helium cooled pebble bed concept

For fuelling of the first generation power plants based on fusion of deuterium and tritium, the latter has to be produced by transmutation of lithium through the neutrons generated in the plasma. Present blanket designs consider solid, as well as liquid lithium compounds, combined with a neutron multiplier. ITER will serve as a test bed for Test Blanket Modules (TBM), which will provide input for the design of blankets for the Demonstration fusion reactor (DEMO) and for later fusion power plants. Such a TBM also closely needs to follow the design of blankets for DEMO and fusion power plants. It is essential to test ITER blanket sub-modules in materials testing reactors.
The neutron spectrum in the HFR forms a realistic environment for the testing of blanket modules. Four helium-cooled pebble bed assemblies with lithium-silicates and lithium-titanates, which closely resemble the major design for ITER's intended TBM, were tested in the HFR before being dismantled in 2005



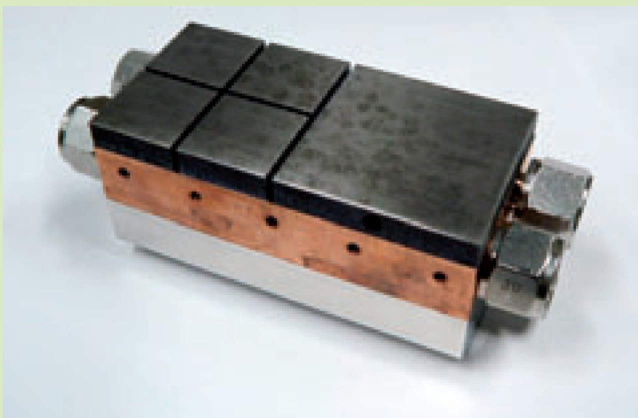


Figure 39 (left) - Primary Wall Module test element for in-pile fatigue testing at HFR

Figure 40 (right) - Prototypical Primary Wall Module produced by EU industry for out-of-pile testing (courtesy EFDA)

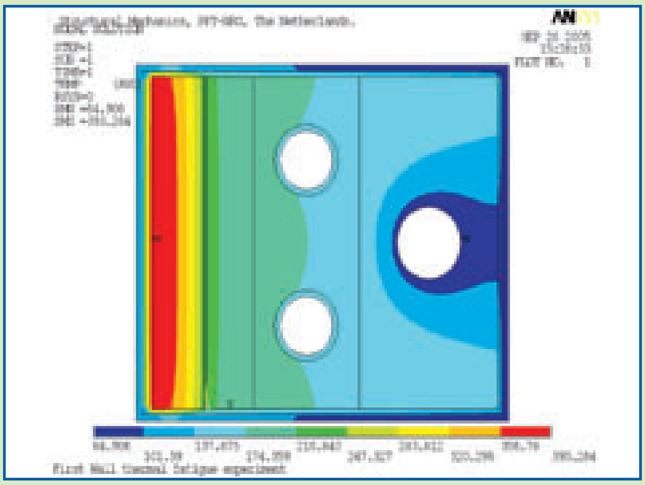


Figure 41 - Temperature analysis for PWM in-pile test

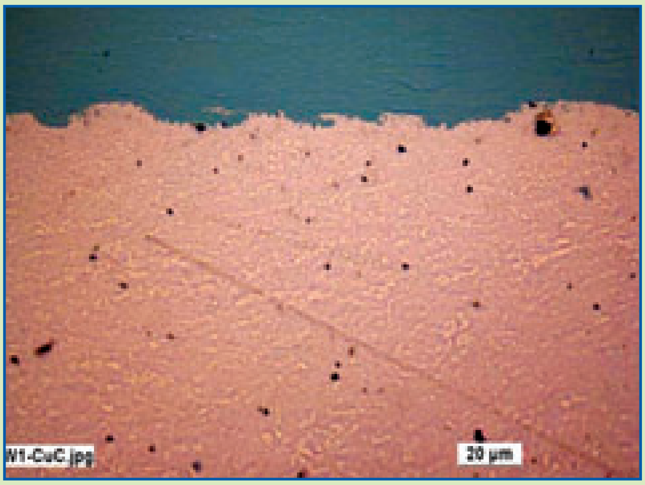


Figure 42 - Innovative bonding technique for tungsten on Cu-alloy (courtesy TNO/NRG)

and 2006. A detailed plan of post-irradiation examinations was developed and tested on a prototype module in 2006. The PIE is to provide possible evidence of gap formation at the pebble-bed wall interface. In addition, a wealth of information can be gathered on material compatibility and TBM relevant instrumentation issues. In addition, modelling has supported analyses of in-pile performance data.

Functional fusion blanket materials

In the EXOTIC (EXtraction Of Tritium In Ceramics) series, irradiation of meta-titanate pebbles from CEA (F) continued. The experiment EXOTIC-9/1 focuses on in-pile tritium release characteristics. In addition, the effect of in-situ oxidation on the permeability of Eurofer-97 has been experimentally simulated with moisturised purge gas. The principle methodology for in-situ oxidation of components for gas-cooled reactors was demonstrated.

Preparation of the HICU experiment (High-fluence Irradiation of breeder Ceramics), aimed at long-term (up to two years) irradiation of ceramic pebbles, is still underway. Following the HEU-LEU conversion of the HFR, uncertainties in the design could be reduced. Furthermore, validation of neutronics were performed to allow rig manufacturing and assembly in early 2006. Japan and USA are partners in the framework of the IEA (International Energy Agency) implementing agreement on Nuclear Technology. Manufacture of the neutron screen and assembly of the specimen stacks could be realised. Selected stacks were scanned with the advanced X-ray tomography technique at the University of Manchester. The images serve the planning and detailing of the post-irradiation examinations scheduled for 2009-2011.

The two high dose irradiations of beryllium specimens, HIDOBE-01 & 02 continued in 2006. The objective of the HIDOBE project is to quantify the long-term behaviour in terms of swelling, creep and tritium retention and validate preliminary model descriptions. Beryllium pebble stacks are irradiated in the HFR for a 2 and a 4-year period. In the framework of the IEA implementing agreement on Radiation Damage Effects in Fusion Materials, partners in the EU, Japan and the Russian Federation provided different grades of beryllium specimens.

In the area of lithium, lead based, blanket concepts, in-pile operation of two LIBRETTO type rigs continued. These are aimed at the permeation characteristics of Eurofer tubes under relevant irradiation parameters, at 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.

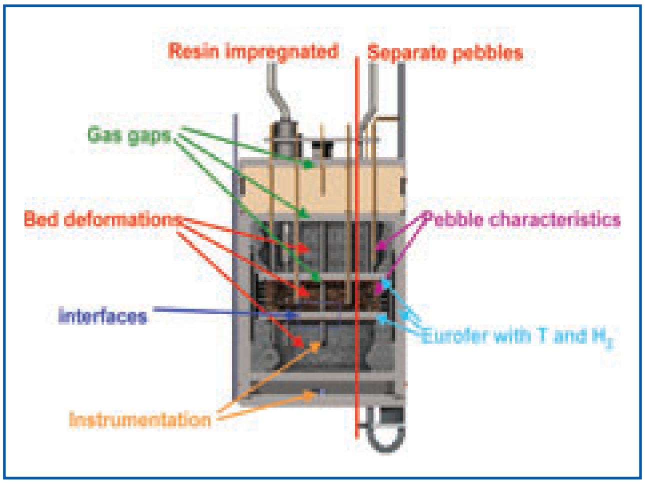


Figure 43 - Cross section of Pebble-Bed Assembly, irradiated in HFR, and key performance issues addressed in the post irradiation examinations

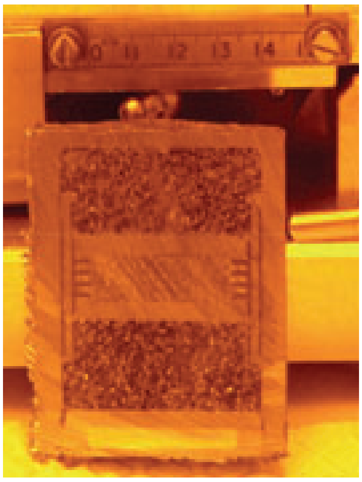


Figure 44 - Cross section of the prototype PBA assembly - preparatory result of P.I.E.

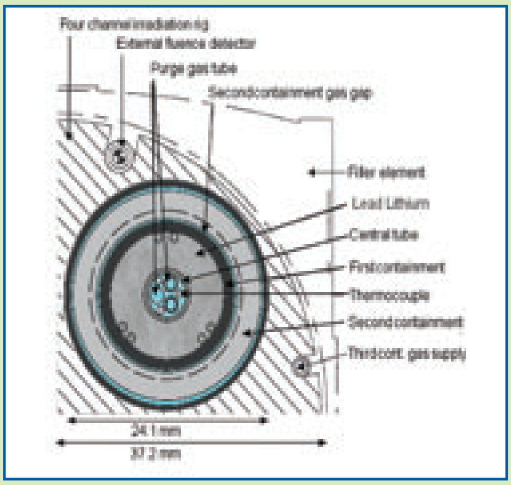


Figure 45 - Cross section of the LIBRETTO-4 type irradiation capsules for testing of blanket concepts with lithium-lead eutectic

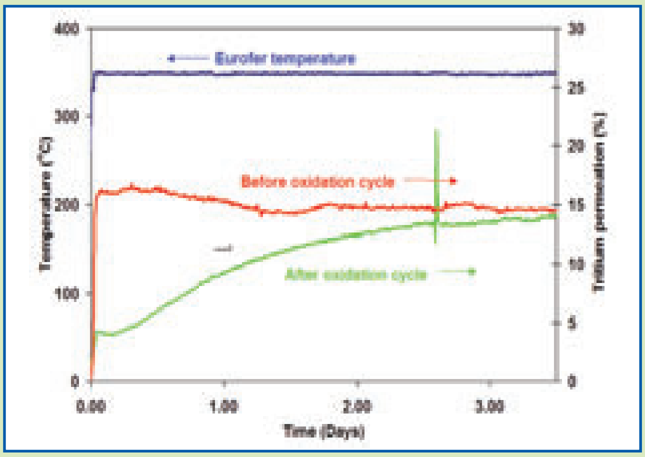


Figure 46 - Evidence of in-situ oxidation process effectively reducing tritium permeation in LIBRETTO-4 experiments in support of the EFDA HCLL concept development.

Structural steel for ITER test blankets

Ferritic, martensitic steels have become the reference structural steel for blankets. An advantage of such steels is that, providing the impurity level can be controlled, they can be made with alloying elements that allow re-processing after less than 100 years. Manufacture of such alloys has been successfully demonstrated by the Japanese and EU steel industry. This class of steels is called Reduced Activation Ferritic Martensitic (RAFM) steel.

A complete set of irradiation projects with post-irradiation testing is necessary to qualify this steel for application in blankets. The first target is the justification for its use in the ITER test blanket modules. In the HFR, a large programme is underway to contribute to the quantification of neutron irradiation effects up to 12 dpa, on RAFM steels. Extensive post-irradiation testing is ongoing at NRG's Hot Cell Laboratories, including fracture mechanics, Low-Cycle Fatigue with hold-times and Fatigue Crack Propagation with hold-times.

The SUMO-09 capsule irradiation with three temperature levels (250-300-350°C) reached 2.5 dpa in 2006. The post-irradiation testing involves small size specimen technology and crack-propagation in sandwich systems with compliant layers.

The irradiation stress relaxation experiments STROBO-06 and -07 were performed in 2006. The rigs include pre-stressed bolt assemblies and bent-strips. A new task was also started on the characterisation of the European Eurofer ODS reference batch under irradiation up to 2.5 dpa. SUMO-type capsules were manufactured for three temperature levels (300-450-500°C).

Silicon carbide ceramic structural material

Providing that the oxide dispersion strengthening of next generation steels is effective, blankets based on steels will allow operational temperatures up to 650°C. Another 100°C can be further gained through the use of nano-microstructure stabilisation. However, given that the upper operating temperature of steel will be reached at around 750°C and that higher thermal efficiency can be obtained at operating temperatures over 1000°C, interest is growing in structural materials allowing such operating temperatures. Silicon carbide ceramic composites are candidate materials, which present attractive strength properties up to 1000°C, but also display some drawbacks that need to be addressed:

- low heat conductivity after neutron irradiation;
- strength reduction by neutron irradiation;
- low toughness;
- limited leak tightness.

The earlier SICCROWD irradiations between 600°C and 950°C and the subsequent Post–Irradiation Examinations, formed the basis for a follow-up project with new 2-D and 3-D composites. It also includes a collaborative activity with CEA, where an irradiation experiment is planned at OSIRIS. NRG also started preparations for the ExtreMat Integrated Project that serves both fission and fusion applications of CC and SiCSiC. A hybrid blanket design using steel girders with large parts made from silicon carbide may be the nearest application of such material in fusion power development. SiCSiC is also candidate for support structures and potentially for control rods in advanced High Temperature Reactors.

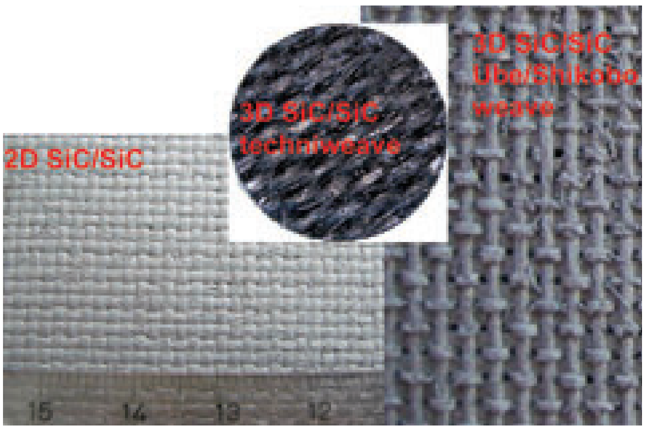


Figure 47 - Pictures of 2D and 3D SiCSiC composite produced by European industry

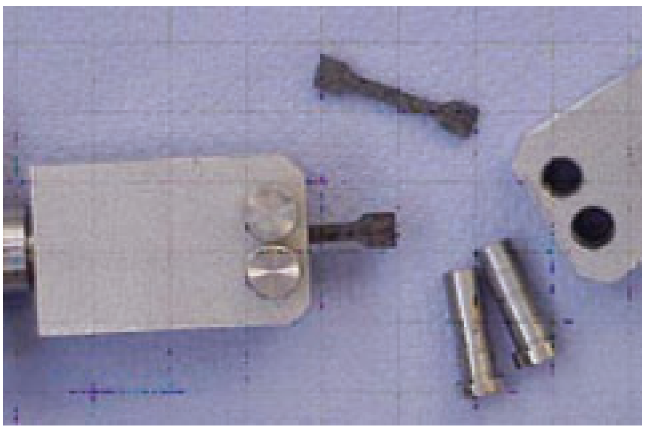


Figure 48 - Development of tensile testing of SiCSiC composite at elevated temperatures

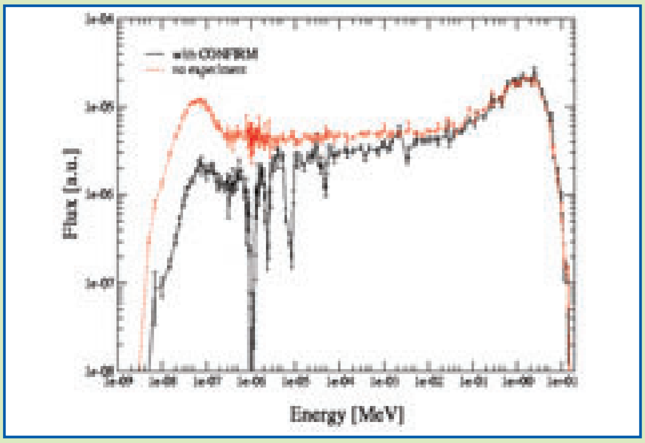


Figure 49 - Spectrum tailoring with hafnium

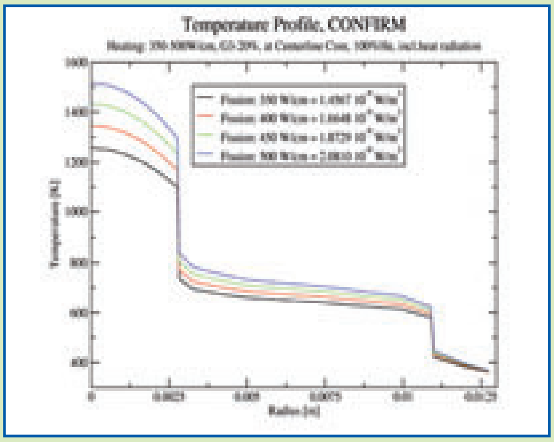


Figure 50 - Fuel temperatures

Partitioning and Transmutation Technologies

FUEL TRANSMUTATION

CONFIRM

Objective

Within the CONFIRM programme (Collaboration On Nitride Fuel IRradiation and Modelling), the properties of uranium-free nitride fuels are investigated for transmutation purposes.

Uranium-free nitride fuels are under development as they possess, compared to oxide fuels, a better compatibility with the industrialised PUREX reprocessing process. They further have the advantage of allowing higher linear ratings, typically a factor of two higher than corresponding oxide or metallic fuels.

The lack of data on uranium-free nitrides, however, necessitates a significant R&D programme before nitrides can be qualified and validated as a suitable fuel.

The CONFIRM programme is therefore dedicated to theoretical and experimental studies on uranium-free nitride fuel characteristics and to test their performance under irradiation to high burn-ups.

Achievements

Within the CONFIRM project, an irradiation is under preparation with 30% plutonium-nitride in a zirconium-nitride inert matrix; $(Pu_{0.3},Zr_{0.7})N$. The CONFIRM fuel pellets have been fabricated by the Paul Scherrer Institute in Switzerland. This fuel, with high plutonium density is developed primarily for applications in fast reactors, such as ADS or GenIV systems.

In order to tune the neutron spectrum to typical conditions in fast reactors, the thermal part of the HFR spectrum is shielded in the irradiation. This is achieved by applying a hafnium shield, which effectively absorbs thermal neutrons. The effect of this 'spectrum-tailoring' is shown in Figure 49: the experiment with the hafnium-shield exhibits a substantial reduction of the thermal neutron-flux (i.e. in the low-energy range), with fast neutrons are passing through the shield undisturbed.

In Figure 50, a cross section is shown of the experiment, depicting the design fuel temperatures during irradiation. Despite the high linear heat rate (up to 500 W/cm), the temperatures remain relatively low during irradiation, maximum 1520 K (~ 1250°C). This can be attributed to the favourable thermal properties of nitride fuels.

The design of the CONFIRM irradiation was completed in 2006 and the start of the irradiation is planned in 2007.

HELIOS

Objective

The HELIOS irradiation (formerly EFTTRA-T5) was originally planned in the framework of the EFTTRA co-operation to investigate the behaviour of minor actinides and long-lived fission products in the framework of transmutation studies. Currently the HELIOS irradiation is part of the FP6 EURO-TRANS Integrated Project on Partitioning and Transmutation, which has been running since Spring 2005.

The main objective of the HELIOS irradiation is to study the in-pile behaviour of U-free fuels and 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 on fuel swelling.

Achievements 2006

After finalisation of the test matrix in 2005, nuclear and thermal calculations were performed and the design was frozen. Contracts for fabrication and assembly were placed. The target capsules will be assembled at JRC-ITU in early 2007, then shipped to Petten for assembly of the irradiation rig with start-up planned for the end of 2007.

TRABANT-02 / SMART

The remaining fuel pin in this TRABANT-02 experiment, named SMART, is composed of two separate fuel pins, one on top of the other, both containing 0.9 g/cm^3 of plutonium, incorporated into an yttria-stabilised zirconia phase, $(Zr,Y,Pu)O_{2-x}$, with one composite fuel type mixed with stainless steel powder acting as the fuel matrix. The experiment has the aim to assess the irradiation behaviour of such fuels up to medium burn-up. The continuation of the SMART irradiation has been delayed but is now scheduled to re-start in early 2007.

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 high radiotoxic ^{210}Po

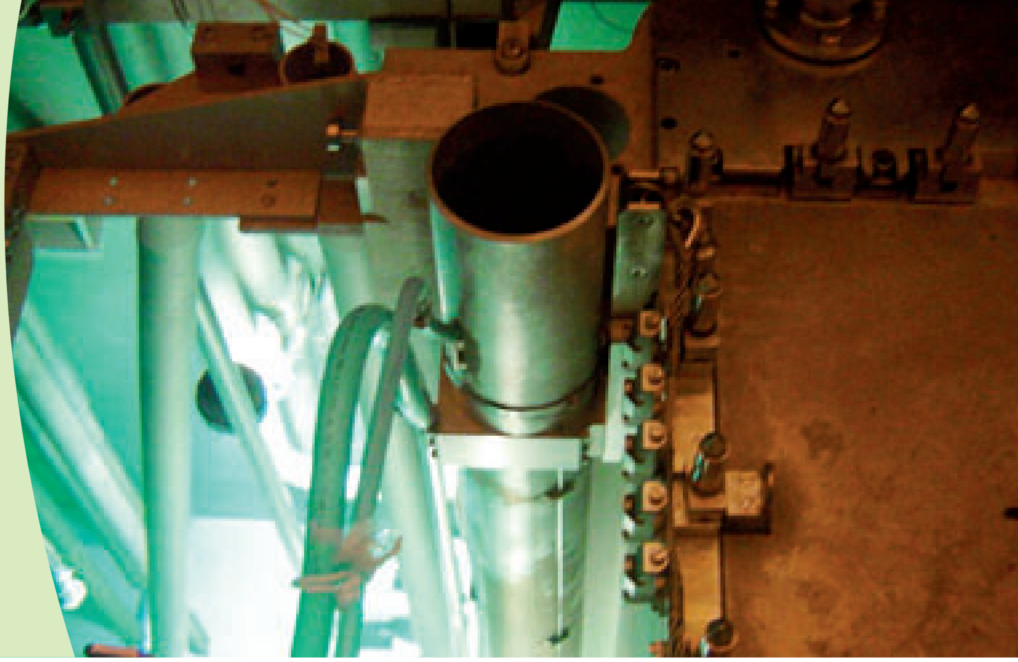


Figure 52 - SIFA in Pool Side Facility

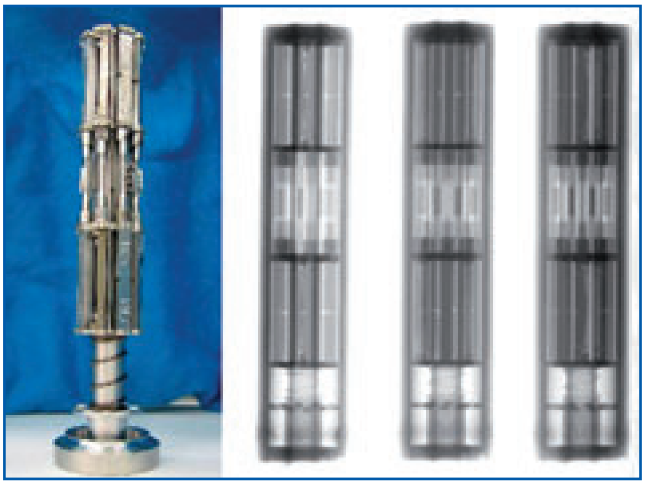


Figure 51 - Assembly of specimens inside IBIS capsule, röntgen image of the three IBIS capsules (300, 500 and capsule for cold testing) before filling with LBE

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.

Achievements in 2006

Fabrication, assembly and welding of three capsules for IBIS have been completed and are ready to be filled at SCK with Lead Bismuth Eutectic. The IBIS design has been completed in detail and sent as an irradiation proposal to the Reactor Safety Committee in July. The Reactor Safety Committee approved the design of the experiment, on the condition that Post Irradiation Testing is well defined and risk evaluation on Polonium handling in the Hot Cells is made before the irradiation starts. After approval of this additional document and the Design and Safety Report, the sample holder and containers will be irradiated at 300 and 500°C in a low flux position in the HFR inside a TRIO 131 rig up to a dose of 2 dpa.

NEUTRON TRANSMUTATION DOPING OF SILICON

Silicon has three stable isotopes: ^{28}Si (92% abundance), ^{29}Si (5% abundance) and ^{30}Si (3% abundance). Neutron irradiation of silicon transmutes ^{30}Si into ^{31}Si, which decays (half-life 2.6 hours) to the stable isotope 31P. This phosphorous doping decreases the electrical resistivity of the semiconductor silicon. Irradiating the silicon in a homogeneous flux causes a homogeneous phosphorous doping of the silicon. This neutron doped silicon has a higher quality than silicon ingots, which are doped during the production of the ingots. Due to its high quality, neutron doped silicon is especially suitable for high power applications.

In 2006 the design, engineering and construction of the Silicon doping Facility SIFA has been completed. SIFA is a facility for the neutron doping of single crystalline silicon ingots with a diameter of 6 inches and a maximum length of 50 cm. The test runs of the SIFA facility have been completed successfully, showing that the specifications on the overall resistivity and the radial and circumferential resistivity gradients can be met.

The 6 inch SIFA facility is in operation together with the SIDO facility, which is used for the neutron doping of 4 inch diameter silicon ingots. SIDO has been used for large scale silicon doping since 2002.

List of Authors

Editorial Team
Editor Responsible: G. Gouwens-van Rijn
Revision: R. Moss
Overall responsible R. May

JRC Main Contributors
L. Debarberis
M. Fütterer
A. Gevers
P. Hähner
R. May
R. Moss
C. Ohms
A. Zeman

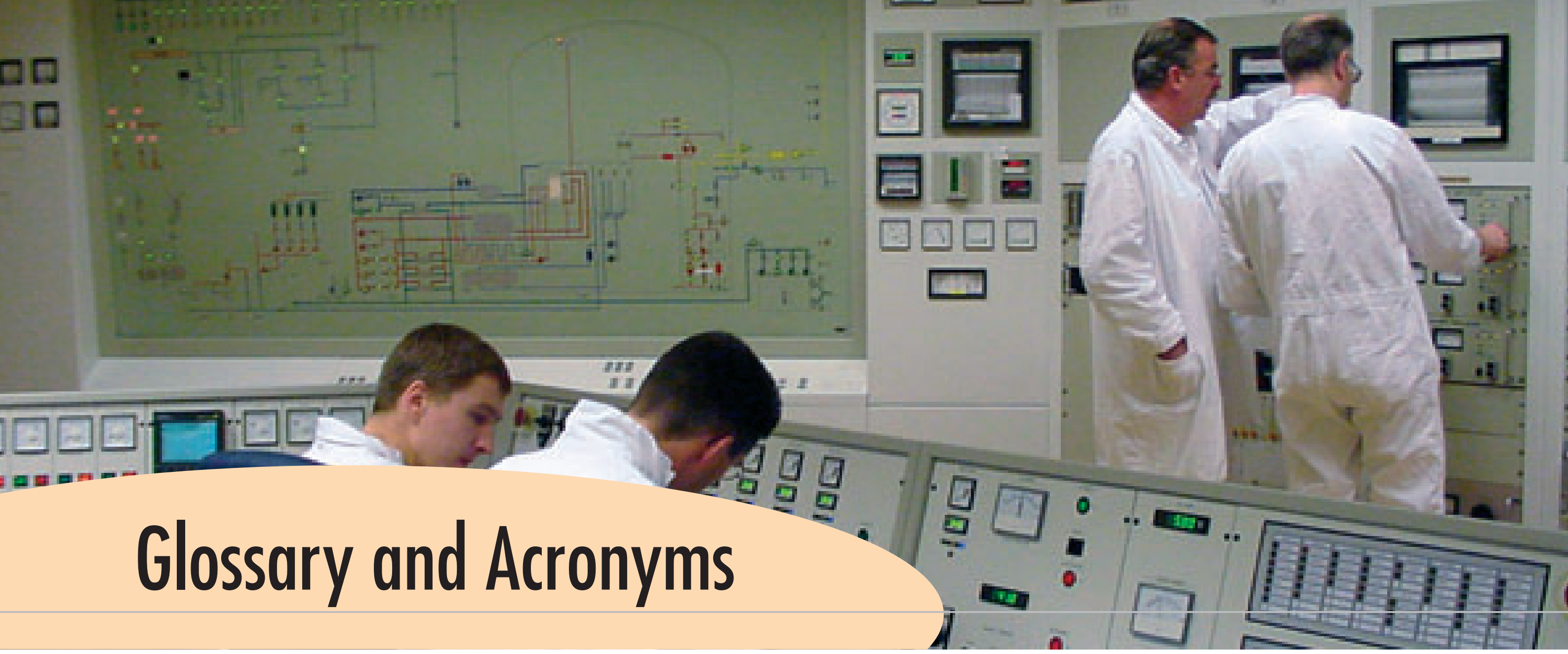
Other JRC Contributors
J. Manten
D. McGarry

NRG Main Contributors
K. Bakker
K. Charlton
S. de Groot
F. Klaassen
J.G. v.d. Laan
L. Magielsen
P. Thijssen
F. Wijtsma

The editorial Team wishes to thank all other JRC and NRG staff who contributed in this report.

Address/Contact
European Commission - Joint Research Centre
Institute for Energy - High Flux Reactor Unit
P.O. Box 2
1755 ZG Petten, The Netherlands
Tel.: +31 (0)224 565151
Fax: +31 (0)224 565615
E-mail: gerda.gouwens@ec.europa.eu
Internet: http://ie.jrc.ec.europa.eu

A list of HFR scientific publications mentioned in this Annual Report can be obtained upon request to the contact person.



Glossary and Acronyms

AE	Acoustic Emission
ADS	Accelerator Driven Systems
AMALIA	Assessment of Nuclear Power Plant Core Internals
AMES	Ageing Materials Evaluation Studies
BNCT	Boron Neutron Capture Therapy
BPA	Boron compound for BNCT
BSH	Boron compound for BNCT
BWR	Boiling Water Reactor
CEA	Commissariat à l'Energie Atomique
CEN	The European Committee for Standardization
COVRA	Centrale Organisatie Voor Radioactief Afval
DEMO	Demonstration Fusion Reactor
DG	Directorate General
dpa	displacements per atom
E&I	Enlargement and Integration
EC	European Commission
ECN	Energieonderzoek Centrum Nederland
EdF	Electricité de France
EFTTRA	Experimental Feasibility of Targets for TRAnsmutation
EIS	Electronical Instrumentation Services
ENSAM	Ecole Nationale Supérieure d'Arts et Metiers
EORTC	European Organisation for Research and Treatment of Cancer
ERA	European Research Area
EU	European Union
EUROTRANS	European Transmutation
EXOTIC	EXtraction Of Tritium In Ceramics
EXTREMAT	New Materials for Extreme Environments
FLUX	Fluence Rate
FP or FWP	Framework programme
FRAME	Fracture Mechanics Based Embrittlement Trend Curves for the Characterisation of Nuclear Pressure Vessel Materials
GIF	Generation IV International Forum
HAZ	Heat Affected Zones
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
HIPOS	High Intensity Positron beam
HTR	High Temperature Reactor
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
IASCC	Irradiation Assisted Stress Corrosion Cracking
IE	JRC Institute for Energy, Petten (NL)
INET	Institute of Nuclear Energy Technology (of the Tsinghua University)
INNOGRAPH	Innovative Graphites
INTERWELD	Irradiation effects on the evolution of the microstructure, properties and residual stresses in the heat affected zone of stainless steel welds
IP	Integrated Project
ISI	In-Service Inspection
ITER	International Thermonuclear Experimental Reactor
ITU	Institute for TransUranium Elements, Karlsruhe
JRC	Joint Research Centre
LCNDF	Large Component Neutron Diffraction Facility
LEU	Low Enriched Uranium
LWR	Light Water Reactor
LYRA	Irradiation Facility for European Network for AMES
MCNP	Monte Carlo Neutron Photon
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide
MTR	Materials Testing Reactor
MYKONOS	Molybdenum Production for Mallinckrodt Diagnostica
NCT	Neutron Capture Therapy
NCTPlan	Neutron Capture Therapy Treatment Planning
NET	Network on Neutron Techniques Standardisation for Structural Integrity
ND	Non-Destructive
NPP	Nuclear Power Plant
NRG	Nuclear Research and consultancy Group
ODS	Oxide Dispersion Strengthened
PBL	Peripheral Blood Lymphocytes
PIE	Post Irradiation Examinations
PISA	Phosphorus Influence on Steel Ageing
PLIM	Plant Life Management
PSF	Pool Side Facility
PWR	Pressurized Water Reactor
R&D	Research and Development
RAFM	Reduces Activation Ferritic Martensitic (steel)
RI	Radioisotopes
RPV	Reactor Pressure Vessel
RSA	Reactor Snel Afschakeling (Automatic Shut-down)
SAFELIFE	Safety of Aging Components in Nuclear Power Plants
SAFETY-INNO	Safety of Innovative Reactor Designs
SANS	Small Angle Neutron Scattering
SCC	Stress Corrosion Cracking
SCW	Super-Critical-Water
SCWR	Super Critical Water cooled Reactor
SEM	Scanning Electron Microscope
SICCROWD	SIC-SiC composites, Chromium and tungsten (W) irradiation
STROBO	Stress Relaxation of Bolt Materials
SUMO	In-Sodium Steel Mixed Specimens Irradiation
TBM	Test Blanket Modules
TEM	Transmission Electron Microscope
TG	Task Group
TN	Technology Network
TRABANT	TRAnsmutation and Burning of Actinides in a TRIOX
TRIO	Irradiation device with three thimbles
TRIOX	TRIO modified for irradiation of MOX fuels
TU	Technische Universiteit
TYCOMO	TYCO Molybdenum
US	United States
VHTR	Very High Temperature Reactor
VVER	Russian Pressurized Water Reactor
WWER	Water cooled, Water moderated Energy Reactor

European Commission

EUR 22757 EN - DG JRC - Institute for Energy
Operation and Utilisation of the High Flux Reactor
Annual Report 2006
Edited by: R. Moss, G. Gouwens - van Rijn, R. May
Luxembourg: Office for Official Publications of the European Communities
2007 - 36 pp. - 21 x 29.7 cm
Scientific and Technical Research Series
ISBN 978-92-79-05568-3
ISSN 1018-5593

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.

In May 2006 the HFR started operation with a fully Low Enriched Uranium core loading. The conversion allows long term fuel supply and offers an important contribution to the global effort of diminishing the use of proliferation-sensitive High Enriched Uranium.
The year 2006 has been a record year for environmental aspects. More than 400 spent High Enriched Uranium fuel elements were removed from Petten, and all high active waste originating from previous years of HFR operation have been removed from the HFR pool.

Other 2006 highlights include:
- *280 operational days*
- *284 visits, 1632 visitors*
- *Several European Networks managed*
- *Various fusion and fission related irradiation experiments carried out*

15

LD-NA-22757-EN-C

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

ISBN 978-92-79-05568-3

9 789279 055683

Publications Office
Publications.eu.int