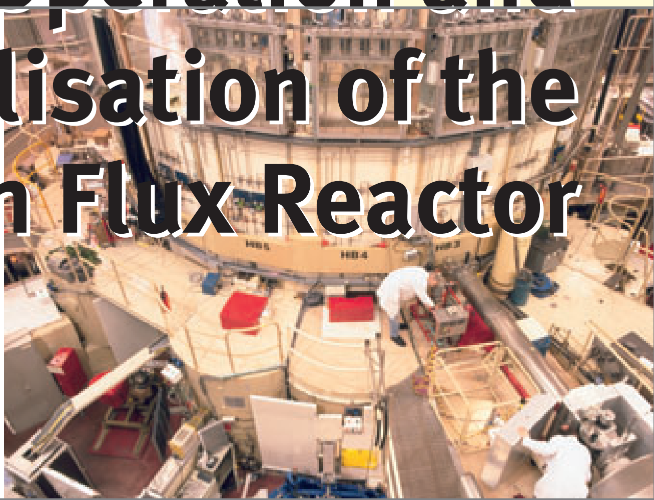
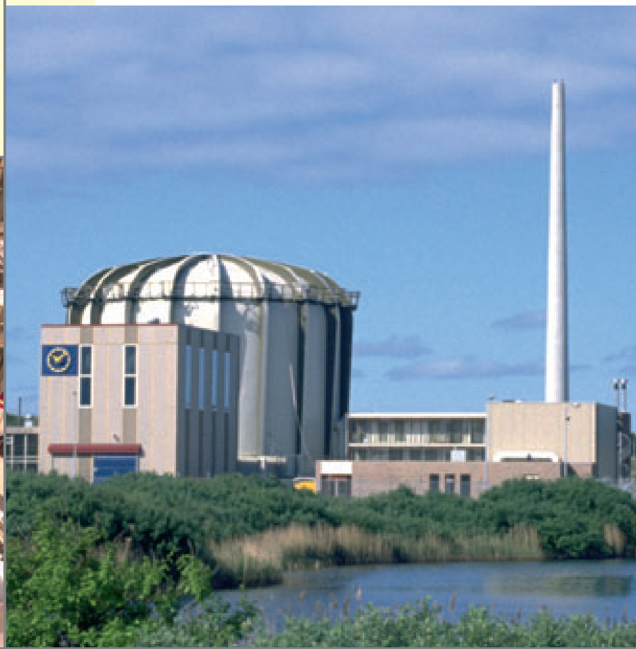
ISSN 1830-5997

Operation and Utilisation of the High Flux Reactor





Annual Report 2005

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Institute for Energy

EUR 22297 EN

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

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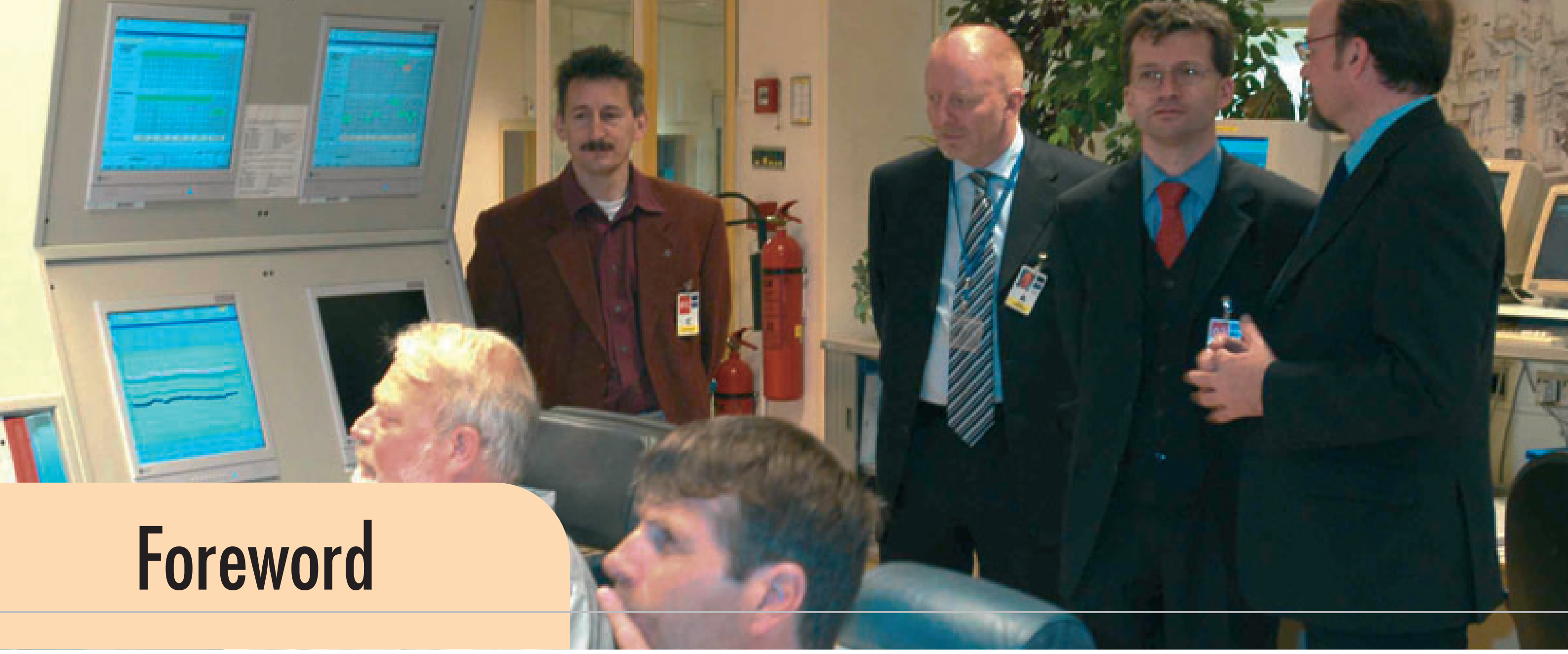
http://www.jrc.ec.europa.eu/

Luxembourg: Office for Official Publications of the European Communities, 2006

ISBN 92-79-02659-3

Printed in the Netherlands, Aranea Offset B.V.

Table of contents



Foreword

The mission of the HFR is to perform research into 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
- 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.

In February 2005 a new nuclear licence for the operation of the HFR has been granted by the Dutch authorities. This accomplishment is the result of more than three years' preparatory work which included a thorough safety re-evaluation of the facility and of its operations against the most updated national and international guidelines, as well as a new set of deterministic and probabilistic safety analyses. The new licence, which is the first renewal after more than 40 years of operation, has been granted to the HFR operator NRG. The JRC's interest in the HFR is focussed on its scientific programmes supporting nuclear safety, health and fundamental research. After the granting of the new licence, the JRC maintains the ownership of the reactor and the responsibility for the final decommissioning, foreseen not earlier than 2015.

Following the effort made during the last three years to enhance the safety of the facility in all its aspects, the JRC requested IAEA to conduct a full-scope INSARR mission to comprehensively assess the safety of the HFR. The inspection acknowledged that the issues identified in the previous 2002 INSARR were resolved and that in many respects the HFR is currently a role model for research reactors worldwide. The improvements implemented in aspects related to Safety Culture received a special mention in the final mission report. The HFR safety management system has been adopted by the IAEA as a model for research reactors and HFR staff is regularly supporting the Agency in the definition of guidelines and in the introduction of similar methodologies in other facilities.

In the second half of 2005 the HFR has successfully started the progressive conversion from high to low enriched uranium, which will be completed in May 2006. The reduction in thermal neutron flux, a known disadvantage of the conversion, has been minimized to around 3%, thanks to an intensive optimization of the conversion process that has been conducted by means of reactor physics analyses through the evaluation of different fuel loading patterns.

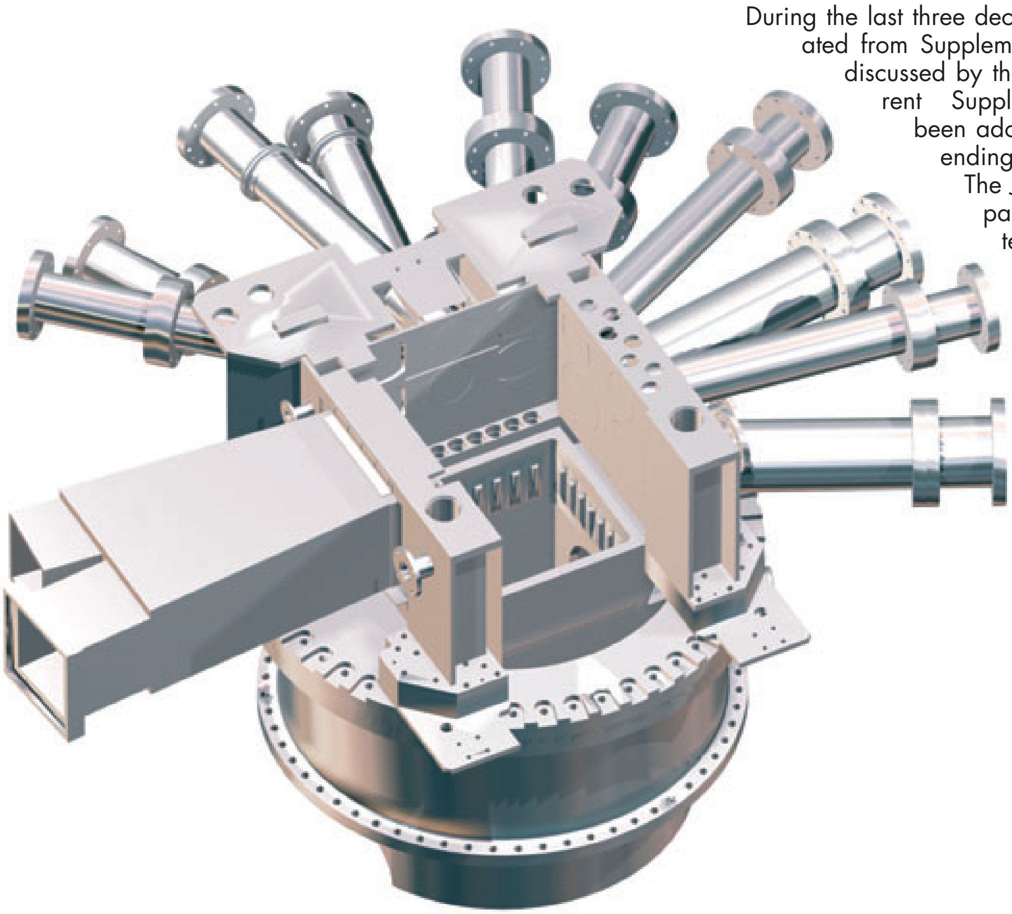
In 2005, the HFR has seen several events concerning the irradiation testing of nuclear fuel. Two irradiations were completed successfully, one is ongoing and four others are under preparation. These irradiation campaigns aim at testing the operational limits of innovative fuel for the U-Pu or the Th-U fuel cycle and for the incineration of minor actinides, and for the fission gas retention capability of high burn-up fuel for high temperature reactors. For the latter type of experiment, a new gas supply and analysis system was commissioned by JRC-IE in the HFR, and a system for post-irradiation safety testing of such fuel was put into service at JRC-ITU. The JRC is currently the only laboratory worldwide that can offer the complete chain for gas-cooled reactor fuel qualification, including irradiation with on-line monitoring capabilities, post-irradiation examinations and safety testing.

On behalf of the HFR Management, we would like to express our gratitude to all staff who have contributed to the excellent performance of the HFR and its related activities, as well as, of course, their fine contributions to this report. I would also like to forward my compliments to our stakeholders who, through their involvement in the HFR, have made again important contributions to another successful year.

Roberto May

Introduction

The High Flux Reactor (HFR) at Petten, managed by the Institute for Energy (IE) of the Joint Research Centre (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 Nuclear Research and consulting Group (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 the HFR as a tool for European collaborative programmes. NRG operates and maintains the plant, under contract, to JRC and, since the 2000/2003 programme, manages the commercial activities around the reactor. As of February 2005, NRG has become the holder of the operation licence granted under the Dutch Nuclear Energy Law. Furthermore each organisation provides complementary possibilities around the reactor activities, such as the hot cell facilities of NRG and 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 been operated from Supplementary Programmes regularly discussed by the European Council. The current Supplementary Programme has been adopted for a period of 3 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 before the end of the current Supplementary Programme. The objective should be to broaden the partnership for the HFR and in particular to allow industry and private research centres to join in the operation of the HFR.

HFR: Reactor Management

HFR Operation and related services

In 2005 the regular cycle pattern consisted of a scheduled number of 299 operation days and two maintenance periods of each 23 days. The reactor vessel In Service Inspection (weld 18) was performed during the summer maintenance period, during which also the Accident Pressure Equalisation (APE) lines were installed on the upper part of the reactor vessel. In reality the HFR has been in operation during 289 days (Figure 1). This corresponds to an actual availability of 96.57% with reference to the original scheduled operation plan. Nominal power has been 45 MW, except shortly during the end of cycle 05.11 and cycle 05.12, with a total energy production of approximately 12834 MWd, corresponding to a fuel consumption of about 16 kg ^{235}U.

At the beginning of the reporting period, the HFR was in operation for the performance of cycle 05.01. Towards the end of the reporting period two power distribution measurements at a reactor power of 500 kW, regarding the LEU-conversion, and at 30MW, regarding the annual reactor-training programme have been carried out. Preparations and executions for the shipment of 210 spent fuel sections to the United States and the modifications of the pool cooling system were successfully performed. Cycle 05.08 was started 48 hours later then originally planned, due to a formal delay of the regulatory permission to start the reactor, which was necessary after the installation of the APE-lines. Both APE-lines were removed while the redundant vacuum breakers on the primary outlet line remained in place.

Table 1 - 2005 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)
2005		MWd	hrs	h.min	h.min	h.min	h.min	h.min	h.min	PD*	Scram	Bq x E+11
01.01 - 25.01	05.01	1094.9	584	00.24	583.32		583.56	16.00	00.04		1	6
26.01 - 22.02	05.02	1155.03	616	01.44	615.42	00.04	617.30	54.20	00.10		1	5
23.02 - 22.03	05.03	1160.67	616	02.54	617.36	00.02	620.32	51.28		7		6
23.03 - 19.04	05.04	1155.16	616	02.10	615.20		617.30	53.30				6
20.04 - 11.05	Maintenance period							528.00				
12.05 - 07.06	05.05	1135.08	616	07.15	602.28		609.43	38.17		1		6
08.06 - 05.07	05.06	1091.70	616	205.02	405.09		610.11	61.45	00.04	1	1	4
06.07 - 02.08	05.07	1133.58	616	02.48	603.49		606.37	64.00	01.23		3	3
03.08 - 24.08	Maintenance period and ISI							528.00				
25.08 - 20.09	05.08	994.12	616	06.12	528.57	00.03	535.12	15.57	96.51		4	3
21.09 - 18.10	05.09	1151.98	616	01.56	612.41		614.37	57.15	00.08		1	4
19.10 - 15.11	05.10	1042.90	616	05.18	555.08	03.33	563.59	67.39	41.22		2	3
16.11 - 13.12	05.11	1019.68	616	03.41	543.24	17.40	564.45	63.43	43.32	1	2	3
14.12 - 31.12	05.12	699.18	432	01.46	381.46	02.00	385.32	46.00	00.28			
TOTAL :		12833.98	7176	241.10	6665.32	23.22	6930.04	1645.54	184.02	10	15	49
Percentage of total time in 2005 (8760 h) :				2.8	76.09	0.27	79.10	18.79	2.1			
Percentage of planned operating time (7176 h) :				3.4	92.89	0.33	96.57					

**PD: Power decrease*

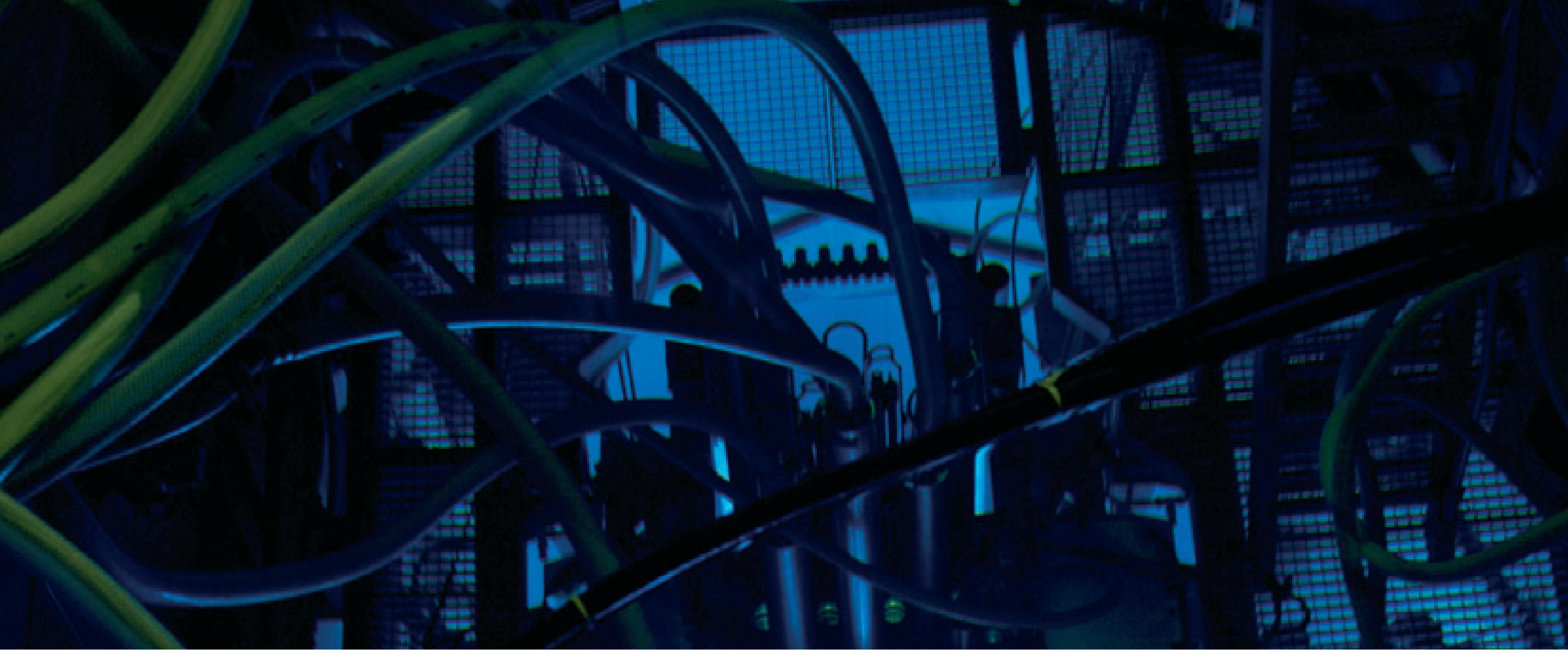


Figure 1 - HFR availability

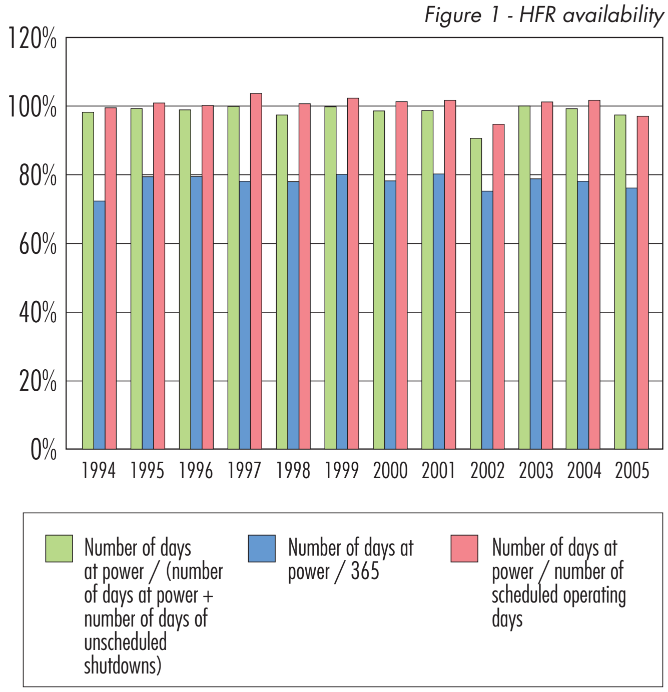
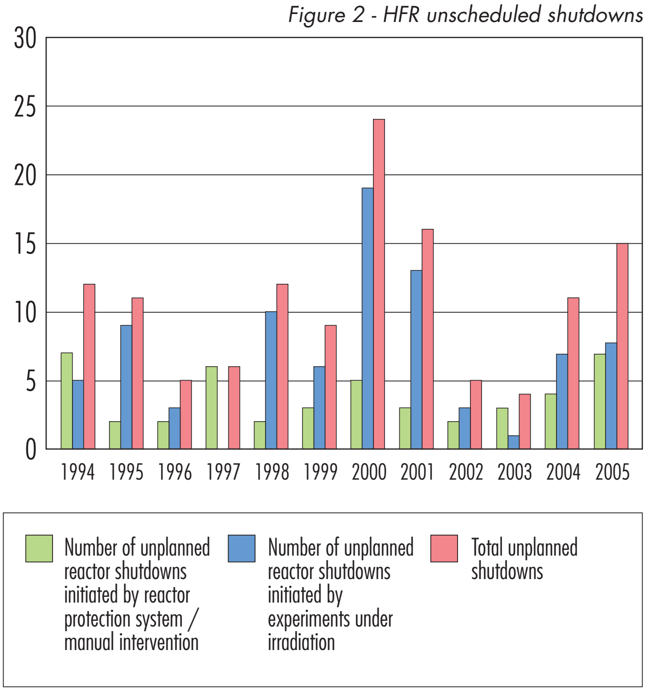


Figure 2 - HFR unscheduled shutdowns



After the scheduled end of all cycles at 45 MW operation, the cycles were directly followed by activities performed in the framework of the regular HFR's operators training.

The detailed operating characteristics for 2005 are given in Table 1. All details on power interruptions and power disturbances, which occurred in 2005, are given in Table 2. It shows that 15 scrams occurred; (see also figure 2). Six of these scrams were due to human intervention, i.e. human error. Technical malfunctioning caused four others, while two scrams were caused by loss of off-site power and the remaining three scrams were due to intervention by safety systems of the experimental devices.

In 2005 many people visited the reactor. Apart from the usual visits of international colleagues and relations in the medical world, the open day during each cycle, attracted many visitors from the public. A total of 1330 people divided over 239 tours were guided through the 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/ ORIGINALPOWER	1	MW	2	3		
2005		hour	hour	hour	h.min	h.min						
13 Jan	05.01	04:17	04:21	04:45	00.04	00.28	AS	0	E	I	Experiment 267-09	The cooling water connection of channel 2 of experiment 267-09 leaked at the coupling between coolant hose and piping. The low pressure caused an automatic reactor shut-down.
31 Jan	05.02	08:32	08:42	08:50	00.10	00.18	AS	0	A	E	UPS	A defective terminal caused a fuse of the VZA-2A group 8 to break down, resulting in an automatic reactor shut-down.
02 Mar	05.03	16:36	16:45	16:50	00.09	00.14	MP	25	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 25 MW during manipulations with experiment FUJI on the PSF.
08 Mar	05.03	14:00	14:06	14:08	00.06	00.08	MP	25	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 25 MW during manipulations with experiment FUJI on the PSF.
09 Mar	05.03	13:30	13:36	13:40	00.06	00.10	MP	20	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 20 MW during manipulations with experiment FUJI on the PSF.
09 Mar	05.03	13:43	13:54	13:56	00.11	00.13	MP	29	E	S	Experiment 324-07/08	The reactor power was reduced to 29 MW during repositioning of experiment FUJI on the PSF.
10 Mar	05.03	21:40	21:48	21:50	00.08	00.10	MP	25	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 20 MW during manipulations with experiment FUJI on the PSF.
16 Mar	05.03	11:32	11:43	11:52	00.11	00.20	MP	25	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 20 MW during manipulations with experiment FUJI on the PSF.
18 Mar	05.03	21:08	21:14	21:17	00.06	00.09	MP	25	E	S	Experiment 324-07/08	By working order the reactor power was reduced to 20 MW during manipulations with experiment FUJI on the PSF.
13 May	05.05	10:30	14:14	14:18	03.44	03.48	MP	30	A	R	Increase of gas activity in containment building	Due to the occurrence of small air bubbles in the pool coolant system an increase of gas activity occurred. The reactor power was decreased to 30 MW as a precaution until the air was released from the pool coolant system.
13 Jun	05.06	11:44	11:48	12:02	00.04	00.18	AS	0	E	H	Experiment 291-02/05)	During flushing of experiment TRABANT a wrong gas mixture caused a temperature excursion.
19 Jun	05.06	14:58	15:02	15:17	00.04	00.19	MP	0	A	R	Secondary system	Secondary pumps switched off automatically on –2.40 m NAP level. To prevent a RSA the reactor power was decreased manually. After a reset of the –2.40 alarm, the reactor power was increased to nominal power.
11 Jul	05.07	14:06	14:11	14:22	00.05	00.16	AS	0	R	H	Safety channels	During loading of experiment 292-02 (TIRO-2) a reactivity excursion occurred by which the safety channels were activated with a RSA as result.
11 Jul	05.07	14:28	14:32	14:45	00.04	00.17	AS	0	R	H	Safety channels	During positioning of experiment 292-01 (TIRO-1) shortly after the previous RSA the safety channels were again activated with a RSA as result.
12 Jul	05.07	18:12	18:16	18:50	00.04	00.38	AS	0	E	H	Experiment 354-01	The experiment 354-01 (TYCOMO) was unloaded while the safety systems were still in operation, with a RSA as result.
28 Aug	05.08	06:30					MS	0	E	H	Experiment 320-09	The BOA of experiment SUMO (320-09) was damaged during unloading of TIRO after which the reactor was manually shut down to remove the experiment from the core.
29 Aug	05.08		08:05	11:19	25.35	28.49						
30 Aug	05.08	04:01	04:05	04:24	00.04	00.23	AS	0	R	I	Primary system	After analysis it appeared to be the adjusted setting of the primary flow set point what caused both scrams.
30 Aug	05.08	10:43	10:48	11:00	00.05	00.17	AS	0	R	I	Primary system	
08 Sep	05.08	02:18	02:25	02:42	00.07	00.24	AS	0	E	I	Experiment 347-01	The outlet coolant connection transition (pipe-hose) of experiment 347-01 (TYCOMO) was squeezed, through which the cool water pressure raised above its set point, with a RSA as result.
26 Sep	05.09	15:56	16:04	16:15	00.08	00.19	AS	0	R	E	Mains	Loss of off-site electric power causing a reactor scram.
23 Oct	05.10	16:30					AS	0	E	E	Experiment 354-01	Protection of electrical pump of HDBEKWS appeared twice, both resulting in scrams. Due to Xenon poisoning the reactor could not be restarted the second time.
25 Oct	05.10		09:48	11:25	41.18	42.55						
28 Oct	05.10	17:58	18:02	18:40	00.04	00.42	AS	0	R	I	Mains on K3C	Power dip on Interlock relay print K3C, with a scram as result.
24 Nov	05.11	09:08	09:13	09:49	00.05	00.41	AS	0	R	E	Mains	Loss of off-site electric power causing a reactor scram.
29 Nov	05.11	17:28		17:30		00.02	AP	38	R	H	Experiment cooling	Accidentally manually closing of a valve of the primary experiment cooling system.
07 Dec	05.11	13:09					AS	0	E	H	Experiment 354-01	During manipulations with experiment TYCOMO (354-01) a positive reactor period occurred by which the safety channels were activated. Due to Xenon poisoning the reactor could not be restarted immediately.

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 - 2005 full power interruptions of HFR

Safety Culture

Activities on safety culture enhancement are continually carried out at the HFR. They aim at a continuous improvement of the organization through a constant learning process (fig. 3). The activities for 2005 have been coordinated by the Safety Culture Working Group (SCWG). The SCWG is a joint committee established by JRC, NRG and the Netherlands Ministry of Housing, Spatial Planning and the Environment, Kern Fysische Dienst (VROM-KFD) in 2002 whose objective is "to assess and improve progressively the safety culture of the HFR organization".

During 2005, the SCWG membership was shared between JRC (2 members) and NRG (5 members). The group met nine times in 2005.

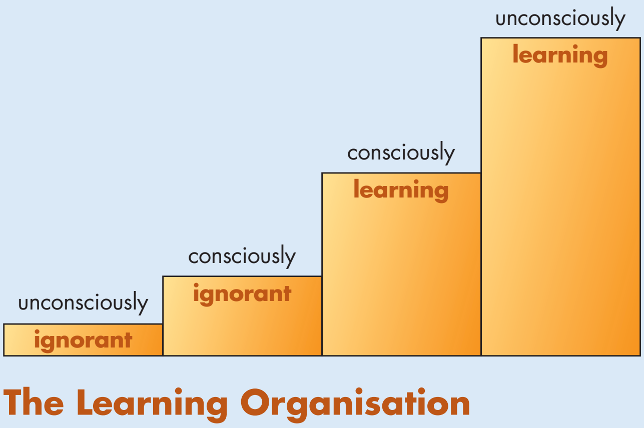
The action plan 2005 was mainly focused on training activities, interviews and improvement teams. During 2005, special focus was given to training activities on human error and root cause analysis. In particular, a three days training course was organized on 14-17 June on Human Error and Root Cause Analysis Techniques with hands on activities on real examples.

Furthermore, as a follow up of the exercise launched by NRG Human and Resources Department on the development of a code of conduct, a round of interviews was performed in March 2005. The focus was mainly on issues of communication and openness. The interviews were performed with different representatives of the organization. They provided useful information to the management and were well received by the participants.

Finally, the SCWG pursued in its attempt to involve staff in improvement actions through the launch of improvement teams on housekeeping.

Safety culture activities at the HFR continue to receive an important feedback from the International Safety Expert Team (ISET) that meets twice a year in order to advice the HFR on safety issues. A new member, an international expert on safety culture, has joined ISET in 2005. This is a further indication of the interest and importance that management place on safety culture enhancement at the HFR.

Figure 3 - Learning steps towards excellence



INSARR

At the joint request of JRC-IE and NRG, the INSARR mission (INtegrated Safety Assessment of Research Reactors) by IAEA for the HFR was held from 13 to 18 February 2005 in Petten. A full scope INSARR was done together with the follow-up of the previous findings of the INSARR 2002 mission. In general, the INSARR team concluded that the operating organization showed a very high commitment to a continuous improvement of the reactor safety and high level of Safety Culture

Good practice

The general objectives of the mission were to conduct a comprehensive safety review of the HFR research reactor, to detect possible problems and to provide advice to solve them to improve the safety. It was decided to have a comprehensive INSARR mission, according to the applicable documents and standards of IAEA. This full scope INSARR was done together with the follow-up of the previous findings of the INSARR 2002 mission to determine the level of implementation of the corrective actions proposed at that time. Thanks to the high dedication of JRC-IE and NRG officials, most of the issues identified in the 2002 INSARR were resolved.
The INSARR review compares the observations and findings with the IAEA Safety Standards and practices found at other research reactors worldwide. The comparison results in recommendations, suggestions, comments and good practices. The outcome of the review is presented in a final report.
The number of recommendations for the HFR is limited. In addition to the recommendations and suggestions, the INSARR team also noticed a number of good practices. The most important good practices are the use of the NRG Integrated Management System and the Management Development training where the emphasis is on leadership, an open attitude and mutual respect.

Integrated Management System

NRG has established this Integrated Management System in which all-important aspects of the complete operation with respect to quality, safety and environment have been combined. The Integrated Management System provides structure and direction to allow NRG the promotion and development of a strong safety culture.
In the future the NRG Integrated Management System will be used as a model used by the IAEA on the implementation of management systems in operating organizations of research reactors.

Management Development training

NRG provided training to all levels of management with special focus on leadership, open attitude and mutual respect. This facilitated the development towards a human / learning organization and provides for a strong commitment of all levels of managers and staff towards safety and resources. The benefits recognized by the involved managers concluded among other things: Improved managers-staff communications, alignment of all personnel to the organization's goals and enhanced safety awareness.

The list of findings (recommendations, suggestions and comments) is currently evaluated and corrective measures will be implemented. The starting point is that all actions originating from the INSARR mission have been completed before the end of 2007. The next INSARR mission at the HFR is planned in 2010.

Fuel Cycle

Figure 4 - Transport to the port of Den Helder

Front end

During 2005, new fuel elements and new control rods were inspected at the manufacturer's site and delivered on schedule. This was the first series of fuel elements and control rods containing low enriched uranium (LEU).
The conversion of the HFR from high enriched uranium (HEU) fuel to LEU fuel started in October 2005.

Back end

After conclusion of a contract with a transport company at the end of 2004 preparations were started for a shipment of HFR spent fuel to the United States. In April / May 2005 five transport containers were loaded with 210 spent fuel elements and transferred to the port of Den Helder in the Netherlands in the second half of May for shipment to the US. In early June the spent fuel arrived safely at the Savannah River Site. So many HFR spent fuel elements had never before been removed in a single shipment.

Also in 2005, new MTR2 baskets were delivered for spent fuel shipments to COVRA. Furthermore a new MTR2 licence for higher burn-up fuel was issued by the German authorities. Following validation by the Dutch authorities, another spent fuel shipment to COVRA took place before the end of the year. In addition a transport licence was issued by the Dutch authorities for spent fuel shipments to COVRA in the coming years.

HEU-LEU CONVERSION

In October 2005, the conversion of the HFR from high enriched uranium (UAl_x) fuel to low enriched uranium (U_3Si_2) fuel was started, with completion planned in May 2006. The conversion will have only a marginal impact on the reactor's operation. The reactor has a total of 33 fuel rods and six control rods. The initiative contributes to the worldwide efforts to limit the use of the proliferation sensitive high enriched uranium. The Dutch government issued a new nuclear energy licence for the reactor in February 2005, including the use of LEU fuel.

The reload pattern of the core was optimised in order to maintain the optimal nuclear characteristics of the irradiation positions. In the figures below calculated neutron fluence rates and flux ratios i.e. LEU:HEU valves, are given.

Core management

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

Figure 5 - Absolute fluence rate values

		A	B	C	D	E	F	G	H	I
	1									
	2				1.22E+14 3.13E+14		8.70E+13 8.02E+13		5.42E+13 3.76E+13	
1.78E+14 3.46E+13	3			1.32E+14 1.74E+14		1.03E+14 1.35E+14		6.23E+13 8.68E+13		
1.52E+14 4.37E+13	4								6.07E+13 6.16E+13	
1.50E+14 4.42E+13	5			2.92E+14 1.77E+14		2.37E+14 1.37E+14		7.45E+13 1.02E+14		
1.42E+14 4.11E+13	6								5.91E+13 6.20E+13	
1.59E+14 3.00E+13	7			1.32E+14 1.73E+14		1.89E+14 1.15E+14		5.75E+13 8.36E+13		
1.55E+14 1.67E+13	8				2.01E+14 9.48E+13		8.26E+13 7.55E+13		5.17E+13 3.74E+13	
	9									

Beryllium Fuel element 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

		A	B	C	D	E	F	G	H	I
	1									
	2				0.82 1.03		0.78 1.07		0.85 1.13	
0.97 1.00	3			0.92 0.96		0.81 0.93		0.69 1.04		
0.97 0.99	4								0.78 1.00	
0.97 0.98	5			0.90 0.89		0.84 0.83		0.73 0.94		
0.98 0.99	6								0.77 1.03	
0.99 1.02	7			0.95 0.98		0.90 0.95		0.68 1.05		
1.02 1.07	8				0.94 1.07		0.80 1.08		0.85 1.20	
	9									

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

Visits and Visitors

January	18	Dutch Board of Governor member Mr. J. Nieuwenhuis, Director Innovation Structure, Ministry of Economic Affairs	
	19	Member of European Parliament Mrs. Jordan Cizelj	
February	01	Environment Department Gemeente Zijpe	
	10	EdF Inspector General for Nuclear Safety, Mr. P. Wiroth	
April	12	Mr. Jean Graff, Luxembourg Ambassador to the Netherlands	1
	13	Traditional annual visit of students of the 7th year (with option physics) of the European School	
	18	Mr. W.H. Cullen Jr., US Nuclear Regulatory Commission	
May	28	Site Open Day together with ECN and NRG; 2.500 visitors	2
June	13	IE Scientific Advisory Group Nuclear Safety	
July	07	Mr. Janez Potočnik, Commissioner of Research	3
October	21	Member of European Parliament Mr. Jerzy Buzek	4
	23	Prof. Chi Guo-chung, Deputy Minister National Science Council, Taiwan	

Workshops and seminars

January	26-28	A three-day seminar on the protection of nuclear facilities against sabotage, co-organised by IAEA and JRC
April	25-29	The 5th International Conference on Isotopes (5ICI) was held in Brussels, Belgium. With over 300 participants and more than 200 scientific contributions, 5ICI was a considerable success
October	05-06	Workshop on Design and Assessment of Radioactive Waste Package
November	23-24	The 2nd NET-PECO workshop on Industrial R&D, Material properties and strain/stress measurements, Neutron methods for engineering applications and residual stress modelling
	11-12	Workshop on "The Requirements for BNCT at a Nuclear Research Reactor": as part of the Enlargement and Integration programme of the JRC, the workshop was held in Prague. Some 50 participants attended from New Member States and Candidate Countries, who have interests to develop BNCT in their own countries.
December	05	Seminar: "BNCT: Absorbed Dose Measurement in Tissue Equivalent Phantoms" by Dr. Grazia Gambarini (University of Milan)

HFR: The Programmes

HFR as a Tool for European Programmes

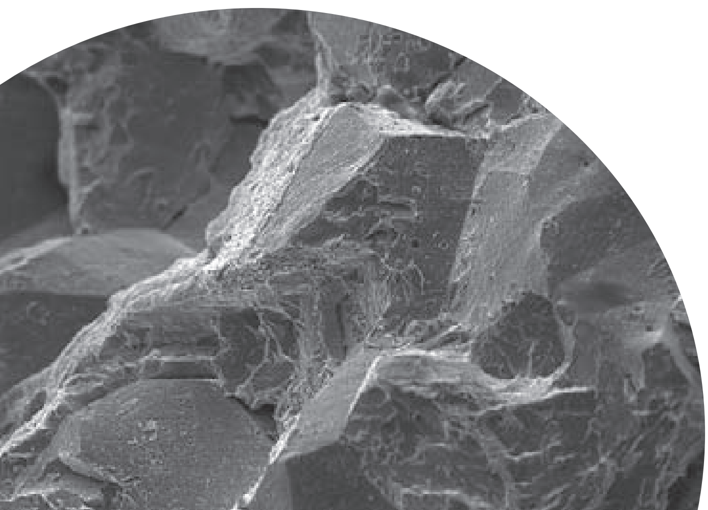
EUROPEAN NETWORK AMES AND SAFELIFE

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

The Action 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 2005 are 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 cover 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 not covered by dedicated R&D work at present, however they are included in the scope of the maintenance optimisation tasks. SAFELIFE is starting a systematic approach to use the available capabilities to actively support advanced reactor materials research and advanced analysis (e.g. behaviour of materials under high loading rates due to 'external events').



SAFELIFE will continue 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 "old" member states and candidate 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 concepts 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 are directly addressing 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. All of which are mainly co-ordinated within the frame of the AMES European Network.

They include: irradiation in the LYRA rig at the HFR of different RPV steels, studies on non-destructive measurements of cladding radiation embrittlement (irradiated in the HFR), based on STEAM method, characterisation of material for IAEA CRP on Mn in high Ni steels (model alloys, model steels and realistic welds projects). Studies on inter-granular fracture, characterisation of materials for future vessels (Cr-Mo-V based alloys), support to large international projects like PERFECT and COVERS, etc.

Within the frame of the JRC Action SAFELIFE and the European Network AMES (Ageing Materials Evaluation and Studies) several activities and developments are ongoing after the successful series of irradiations in the AMES dedicated LYRA irradiation rig. Significant progress towards a mechanistic framework for the understanding of irradiation embrittlement have been booked, in particular with regard

Figure 7 - AMALIA

to the synergism of Cu, P, Ni, Mn on radiation stability of steels. The research is targeted to both Russian-design and Western reactor pressure vessels.

Recent irradiations and results

The PISA project, benefiting from three irradiation campaigns in the LYRA rig at the HFR, is producing important results in order to understand and quantify the influence of phosphorus on steel ageing. Typical PWR, VVER, MAGNOX materials were studied; namely ferritic steels, C-Mn plate, the IAEA reference PWR plate JRQ, a VVER 1000 base metal 15Kh2NMFA, and a number of model alloys supplied by JRC-IE. In particular, it could be demonstrated after irradiation in the HFR that phosphorus segregation is not a critical worry in most technological power plant cases.

The results of the FRAME project, which also included irradiation of samples representative of different reactor systems, both western and Russian-design, are supporting the validation for irradiated materials of novel methods for structural integrity, with in particular the master curve methodology.

A new irradiation campaign in AMES dedicated in the LYRA rig was also prepared to study materials originating from WWER reactors in decommissioning in Germany.

Positron annihilation

A new laboratory to carry out investigations by positron annihilation methods has been commissioned. The rig is using currently a radioactive positron emitting source and the challenge is to create an intense positron beam converting neutrons and gamma radiation generated by the HFR (see page 13) into positrons. A new exploratory project, named HIPOS has been defined to study the feasibility of the rig at one of the HFR neutron beams.

Table 3 **Irradiations in Lyra within AMES**

LYRA I	REFEREE - Nuclear Electric	190 °C for 11.5×10^{22} nm^{-2}
LYRA II	RESQUE / REFEREE	255 °C for 8.17×10^{22} nm^{-2}
LYRA III	MODEL ALLOYS	270 °C for 6.11×10^{22} nm^{-2}
LYRA IV	FRAME	290 °C for 20×10^{22} nm^{-2}
LYRA V	PISA I	200 °C for 5×10^{22} nm^{-2}
LYRA VI	PISA II	290 °C for 5×10^{22} nm^{-2}
LYRA VII	PISA III	290 °C for 18×10^{22} nm^{-2}

IASCC loop in the HFR

The design of a new IASCC (Irradiation Assisted Stress-Corrosion Cracking) loop for the HFR is ongoing. 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 and will solve the critical issue of demonstrating and quantifying the effect of radiation on stress-corrosion processes for BWR, PWR and VVER reactor systems as well as future systems (SCW, super-critical-water).

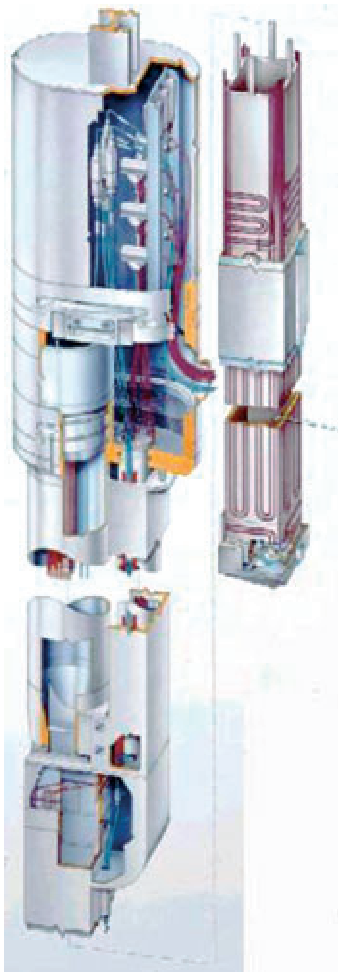
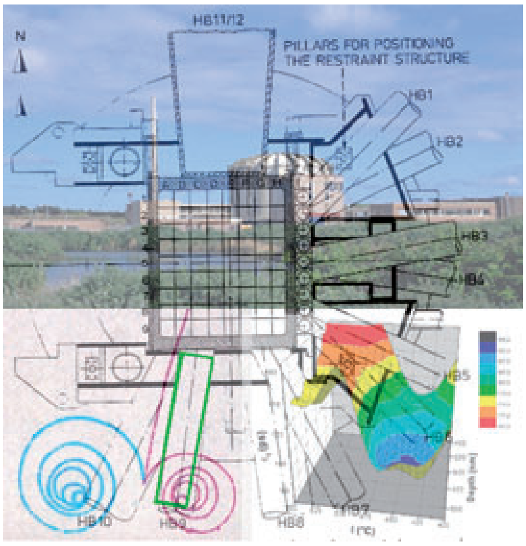


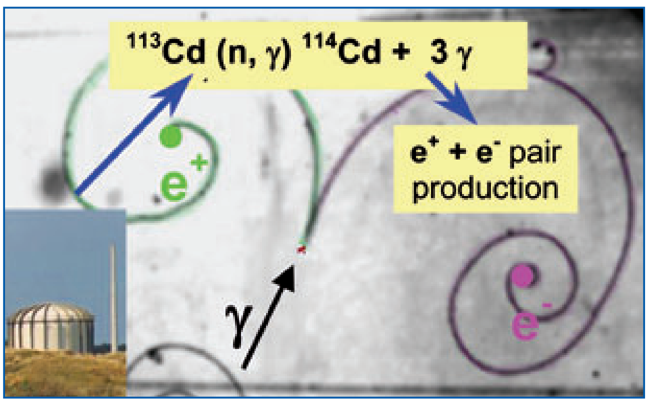
Figure 8 - LYRA irradiation rig



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

The AMES group in the Nuclear Safety Unit is managing the exploratory research related to the HIPOS project. In addition, both the HFR and CEC units are involved in the action as well as external contributors: Helsinki University of Technology (Finland); University of Bundeswehr (Germany); Slovak University of Technology (Slovakia); Delft University of Technology and NRG (Netherlands). The key idea is to build a unique experimental facility with a very high intense positron beam based on (n,γ) and (γ, pair) nuclear reactions at the HFR. The project was accepted and approved in September 2005 by the scientific committees as an exploratory research project in the feasibility phase.

The purpose of this new facility is to make available a new method for investigations and tests based on the annihilation phenomenon of an intense beam of positrons. Such methods are capable to cope with future challenges in many scientific fields, in particular, biotechnology, medicine, space, nanotechnology and material science. For fundamental reasons an image of defects at nanometer resolution by the present generation of micro-beams is impossible. Therefore, a more advanced dual micro-beam system will be proposed, where the defects are stained from previous positrons. A scanning electron beam with nanometer spot size is then sensitive to the stained defects. The facility complements the other neutron based facilities developed at the HFR, including SANS, neutron scattering and the existing positron laboratory. The project will also contribute to the scientific development of the existing Actions of JRC (SAFELIFE, SYSAF, etc.).



An International Scientific Workshop was organized in Bergen, 17-18 November 2005 in the frame of HIPOS. Many European and also Non-European scientists attended this very successful scientific event.

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 new 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 2005, the action comprised the following activities:

- Activities related to the High Temperature Reactor Technology Network;
- High Temperature Reactor Fuel Irradiations;
- Structural material out-of-pile tests for innovative reactors;
- Safety and feasibility studies on innovative reactor concepts.

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 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 the updated website www.jrc.nl/htr-tn.

Achievements in 2005

JRC-IE operates this network, contributed to the coordination of related projects and provided technical input through both institutional and competitive actions. HTR-TN is driven by currently 21 partners and 2 observers from research and industry with further growth anticipated for 2006.

Figure 9 - NET Steering Committee Meeting, Open University, Milton Keynes, UK, June 2005

The network agreement was extended for another five years until 2010.

The network partners efficiently coordinated and supervised the execution of HTR-related R&D projects within the EU's 5th Framework Programme, and prepared a new consistent Integrated Project (RAPHAEL-IP) for the 6th Framework Programme, which started in April 2005 for a duration of 4 years. HTR-TN also provided input for the definition of other EU projects, e.g. on high temperature materials or on hydrogen production technology.

Much of JRC-IE's technical achievements within HTR-TN were proposed as Euratom input to the related GIF projects. Several HTR-TN partners including the JRC were appointed members of high-level GIF bodies and of GIF project management boards.

HTR-TN has updated a strategy paper for the 7th Framework Programme. As long as there is no European plan for the construction of a new demonstration reactor, this paper recommends in particular strengthened cooperation with extra-European HTR projects, the inclusion of the Th-U fuel cycle for enhanced sustainability, coverage of waste minimization techniques, and focus on Combined Heat and Power applications as opposed to pure electricity or process heat applications.

NETWORK ON NEUTRON TECHNIQUES STANDARDISATION FOR STRUCTURAL INTEGRITY (NET)

NET, the European Network on Neutron Techniques Standardisation for Structural Integrity, supports progress towards improved performance and safety of European energy production systems. The state of the art in assessing internal stresses, micro-structure and defects in welded nuclear components, as well as their evolution due to operational loads and irradiation exposure, needs to be improved, before relevant structural integrity assessment procedures can safely become less conservative. The partners of NET have up to now established 3 Task Groups (TG) dealing with the assessment of welding stresses and the impact of thermal ageing on certain steels. By the end of 2005, about 35 organisations are actively participating in the work within these TGs, including eight organizations from the new member states, three organizations from candidate countries, one from Russia and one from South Korea. During 2005 the NET Steering Committee met twice and significant progress has been made in carrying out the work within its TGs (Figure 9).

NET work programme on development and execution

- ***TG1 – Single Bead on Plate Weld***
  The purpose of this Task Group is to perform, by experimental and numerical methods, a thorough assessment of the three-dimensional residual stress field around a single weld bead laid down on a small stainless steel plate. As most experimental and numerical work had already been performed, a phase 1 report on the numerical round robin results has been drafted, which is going to be issued by British Energy in early 2006. Based on the outcome, a problem definition for a numerical analysis, phase 2, has been submitted and partners have already started their analyses. In addition, the experimental protocol has been amended, and such additional tests are performed by partners who have joined NET at a later stage. The NET steering committee has agreed that the work performed by all TG1 participants would be published in form of a special issue of an international journal. This work commenced at the end of 2005.

- ***TG2 – Assessment of post-weld stress relief heat treatments***
  Experimental investigations of the post-weld heat treatments in ferritic steel letterbox repair welded specimens were continued in 2005 with measurements by neutron diffraction performed at FRM-II, Munich. These measurements confirmed the findings of the earlier tests by JRC-IE at the HFR. The steering committee agreed on how to proceed with these specimens, in particular with a view to the cutting of reference samples (Figures 10 and 11).
  An auxiliary round robin exercise has been initiated with the production of test specimens at the premises of one of the NET partners. Low alloy steel plates have been excavated and the excavations filled with three longitudinal beads lying one on top of the other. Four specimens have been made available to NET. In the course of the year preliminary experimental and numerical analyses have been performed by NET partners. The experimental protocol and the problem definition for numerical analyses are in preparation and should become available in 2006.

- ***TG3 – Assessment of effects of thermal ageing to case duplex stainless steels***
  Two NET partners, JRC-IE and INR-Pitesti (RO), have made

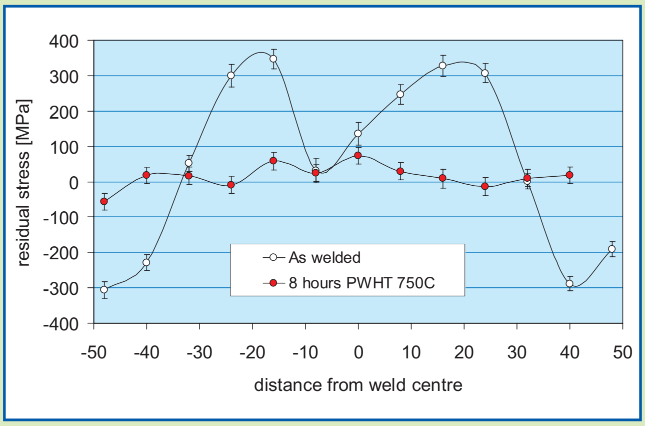


Figure 10 - Longitudinal residual stresses in the 18 bead weld - scan across the weld at mid-length at 3 mm below welded surface (NET TG2)

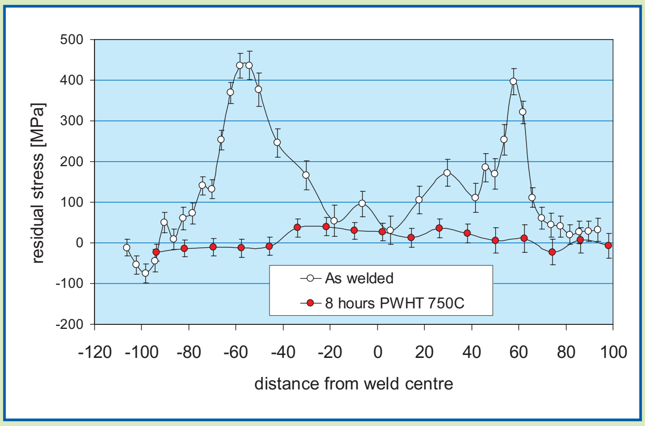
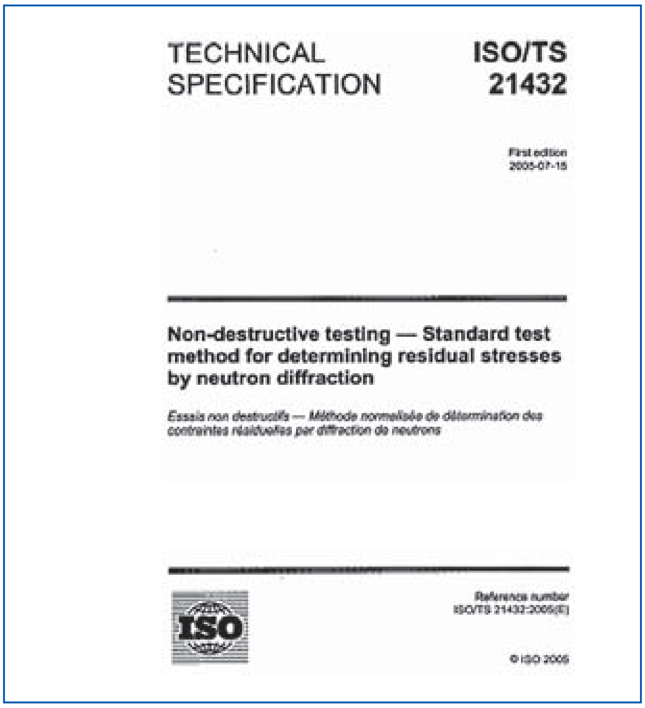


Figure 11 - Longitudinal residual stresses in the 18 bead weld - scan through the weld parallel to welding direction at 3 mm below welded surface (NET TG2)

considerable progress in the (re-)commissioning of their Small Angle Neutron Scattering facilities. They agreed to jointly perform a small round robin exercise on thermally aged steel specimens provided by ENSAM, in accordance with an agreed protocol to be drafted by INR. Data analysis for both facilities will be performed with support from the National Institute for Materials Physics, Bucharest. Experimental work is planned to start in the middle of 2006.

SIANET

In 2005 the Interest Group called Structural Integrity Assessment based on Novel Experimental and advanced modelling Techniques (SIANET) within the European Aeronautics Science Network (EASN) was established amongst the NET members. The Interest Groups within EASN have among their objectives the identification of the research capabilities existing across Europe, and the exchange of information on research opportunities. The formal kick-off of SIANET took place during a dedicated one-day workshop hosted by JRC-IE, with participation of a representative from the aerospace industry and several members of the EASN.


TECHNICAL SPECIFICATION

ISO/TS 21432

First edition 2005-07-15

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

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

Reference number ISO/TS 21432:2005(E)

© ISO 2005

Standardisation Activities

After almost ten years of international/European effort (with significant involvement of JRC-IE) in pre-normative research and subsequently standards drafting, CEN and ISO have adopted and issued in 2005 the Standard document on a "Standard Test Method for Determining Residual Stresses by Neutron Diffraction" (Figure 12). The document is being published now by the national standards organisations in three languages. The corresponding references are:

- Technical Specification ISO/TS 21432, First edition 2005-07-15, Non-destructive testing – Standard test method for determining residual stresses by neutron diffraction, Reference number ISO/TS 21432:2005(E);
- (Vornorm) DIN ISO/TS 21432, Ausgabe: 2005-11 Zerstörungsfreie Prüfung - Standardprüfverfahren zur Bestimmung von Eigenspannungen durch Neutronenbeugung, Deutsche Fassung CEN ISO/TS 21432:2005;
- Essais non destructifs - Méthode normalisée de détermination des contraintes résiduelles par diffraction de neutrons, ISO/TS 21432:2005.

NET related shared cost activities

ENPOWER – Assessment of novel methods for weld repair; technical work completed in 2005.
INTERWELD – Investigation of irradiation induced material changes in the HAZs of RPV welded internals; facility set-up completed in 2005, execution of strain measurements in irradiated test pieces delayed until 2006.

Other NET activities

In 2005, a new contract for third party work was signed for residual stress investigations in welded nuclear components at the HFR neutron beam facilities. The award of this contract was based on similar work performed by the HFR/NET team in 2004 for the same contractor.
A proposal has been submitted for participation of the NET team in an IAEA driven collaborative research project on enhanced utilization of available research infrastructures (reactors) and their residual stress measurement capabilities. The IAEA decision on the submitted proposals is expected for the first half of 2006.

Figure 12 - ISO/CEN Standard on Residual Stress Determination by Neutron Diffraction published in June 2005

HFR: The Programmes

HFR as a Tool for Medical Applications

BORON NEUTRON CAPTURE THERAPY - BNCT

Background
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.

The first clinical trial on BNCT in Europe was started at the HFR in October 1997. Other reactor centres in Europe that are now performing BNCT, include the FiR-1 reactor Otaniemi (Finland); the LVR-15 reactor Rez (Czech Republic); the TRIGA MkII reactor Pavia (Italy) and up until recently, the R2-0 reactor Studsvik (Sweden). Unfortunately, the Swedish programme has been halted due to the permanent shut down of the Studsvik reactors – alternative solutions are being sought elsewhere. Outside Europe, BNCT continues at 2 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 and in many of the New Member States and Neighbouring Countries.

In the meantime, research into various topics of BNCT continue within the group, including advanced dosimetry techniques, gamma spectroscopy with patients and developing methods towards the treatment of liver cancer and rheumatoid arthritis with BNCT. Furthermore, the group have been active in the organisation of workshops on BNCT as part of the Enlargement and Integration programme of the JRC.

JRC Institutional Programme on BNCT
The research and development activities of BNCT at Petten are supported in the JRC's Institutional Research programme. Notable progress has been made in the following activities:

Beam dosimetry
A campaign of measurements using the so-called paired ionisation technique, principally using TE(TE) and Mg(Ar) chambers, was started by one of the BNCT Group's Ph.D. students. 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. 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 (see Figure 13) using the reactor physics code MCNP, in order to obtain detailed calculations into, amongst others, the influence on measurements of neutron capture in the chambers themselves.

Application to different types of tumours: liver cancer
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

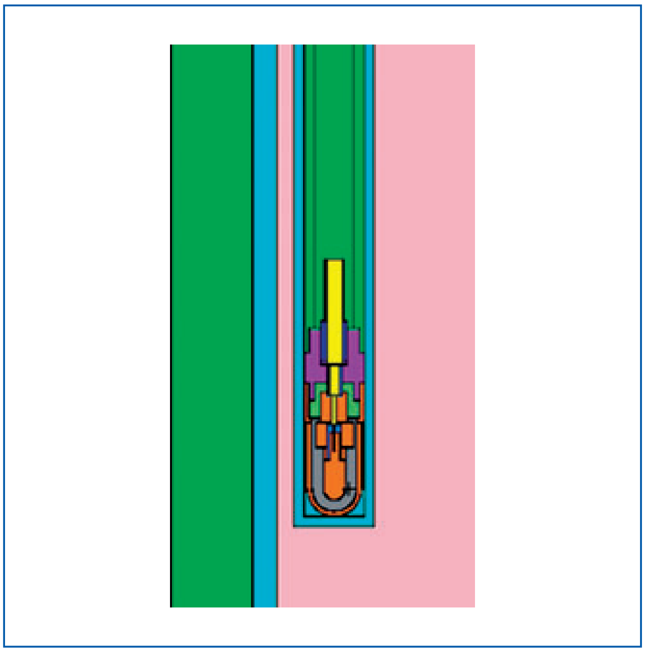


Figure 13 - MCNP Model of an ionisation chamber, in water, next to the wall of the PMMA phantom

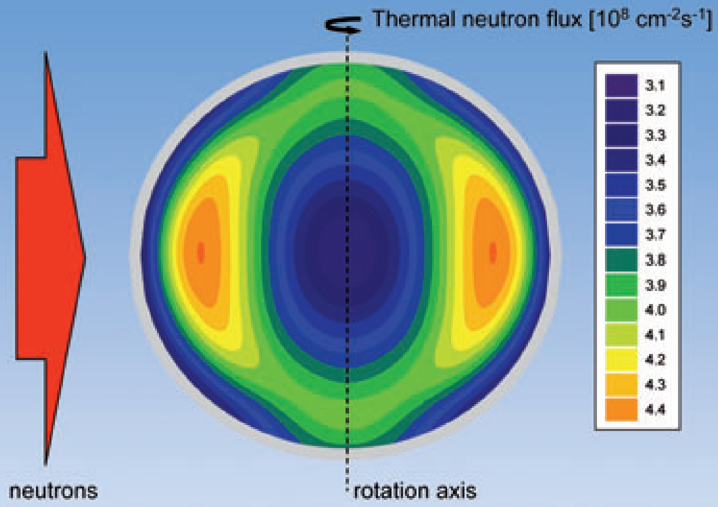


Figure 14 - Thermal neutron distribution throughout the liver in the spheroid-shaped holder. The required fluence can be achieved in less than 3 hours irradiation

Japan, the application of BNCT is performed for a variety of brain tumours, melanoma metastases at many locations in the body, 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-corporal 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 implantation back into the patient, studies are underway at Petten in collaboration with the University Hospital Essen to perform a similar treatment at the HFR.

The major difference between the HFR and the facility at Pavia is that the HFR beam is predominately, a forward directional beam of epithermal neutrons, as opposed to an almost pure thermal neutron beam (or field) in Pavia. The main task at Petten was to construct a facility, which would hold the liver during treatment and would give a homogenous thermal neutron distribution throughout the liver. Design calculations showed that this can be reasonably achieved (see Figure 14) in a spheroid shaped holder, which would rotate during irradiation. The facility was built during 2005 (see Figure 15) and has been subject to validation studies at the end of the year. This included measurements using activation foils and gel dosimetry, as well as purchasing the necessary ancillary equipment to create the required thermal conditions during the irradiation in order to maintain the liver at a constant 4°C.

The gel dosimetry 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. Therefore, this method gives an indication of the thermal neutron flux and the doses along pre-defined axes in the plane of the gel dosimeters, which are positioned in the liver holder and surrounded with water (see Figure 16). The work was performed in December 2005. Initial results are good, but the more detailed reporting is pending.

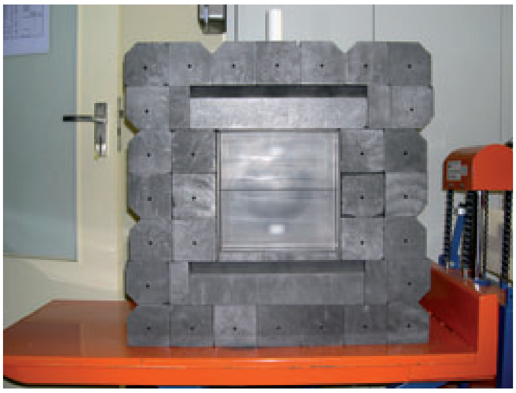


Figure 15a - Liver holder, placed in PMMA block

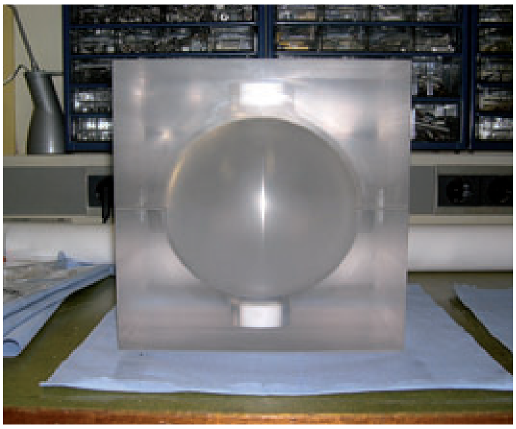


Figure 15b - Block and holder placed in graphite cage

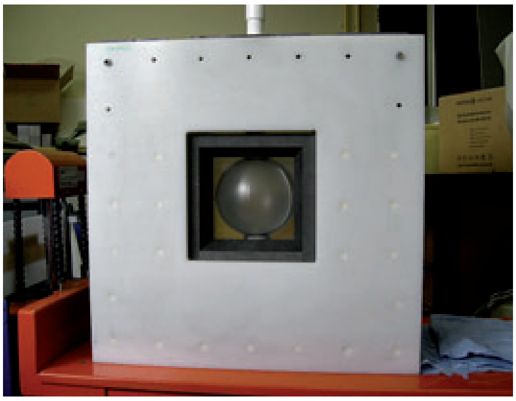


Figure 15c - Beam-eye view of final configuration, covered with polyethylene sheet

Figure 16 - Gel dosimeter being fixed into liver holder prior to irradiation

Application to non-cancerous diseases - rheumatoid arthritis

Rheumatoid arthritis is a disorder that affects joints and the surrounding tissues, including cartilage degradation and osteoarthritis (both cartilage degradation and cartilage synthesis at undesired locations). It is known that rheumatoid arthritis is characterised by chronic inflammation in the joints and that the synovial layer covering the insides of the joints contribute highly to the damage and that these layers contain significant numbers of macrophages. From parallel studies by the University of Delft, it has been found that liposomes can concentrate in the macrophages. Hence, by attaching boron to the liposomes, boron would be transported to the macrophages, which following BNCT would cause destruction of the macrophages, thus relieving pain and eventually over time, be able to control the degree of inflammation and cartilage destruction. In collaboration with the Universities of Nijmegen and Delft, a study is underway to investigate this effect. Several irradiation experiments were performed during the year. The initial results are very promising and further studies, under the auspices of a JRC Exploratory Research project will continue in 2006.

Clinical trials on BNCT

From previous Framework Programmes, three clinical trials on BNCT were supported. 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.

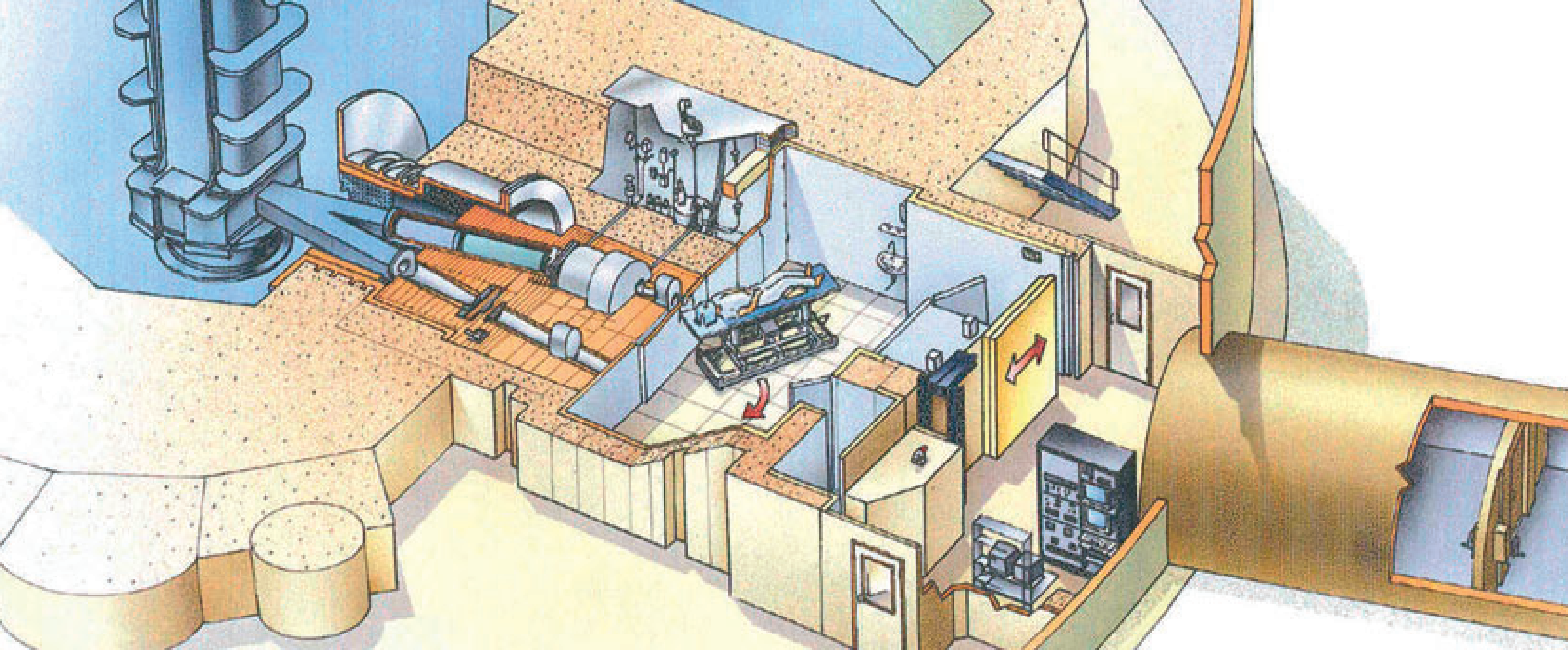
- ***EORTC Protocol 11001: ^{10}B-uptake in different tumours using the boron compounds BSH and BPA***
  This trial looks into the possible uptake of boron into different tumours, including thyroid cancer, head and neck cancer and liver metastases. If successful in terms of significant uptake of boron 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 2005 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.

- ***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 2005, a patient was treated with over 20 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 5 beams on 2 consecutive days.

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:

- Visit to the JRC and the HFR by the EdF Inspector General for Nuclear Safety. There was particular interest in BNCT and possible collaborative discussion with EdF for the future (February);
- The BNCT clinical trials are performed under the auspices of the EORTC. The annual meeting of all EORTC research groups, of which BNCT is one, was held in Brussels (March);
- Invited Lecture (Ray Moss): CERN, Geneva – "Boron Neutron Capture Therapy (BNCT), a promising neutron therapy for the treatment of inoperable cancers: status of the clinical research and recent developments" (April);
- Monte Carlo Seminar – University Hospital Essen - Treatment planning (TP) is a critical part of BNCT. IE Petten currently use 2 different codes. Newcomers to BNCT (especially Mainz University, who are included in the liver project) have no experience in TP. This workshop covered the general TP needs and was valuable experience to the IE/JRC BNCT students and technical staff (May);
- 19th Nuclear Physics Divisional Conference: "New trends in nuclear physics applications and technology", Pavia University. The conference had a number of topical sessions related to nuclear physics applications. Two sessions were devoted to BNCT, with a number presentations on new innovations with accelerator sources, a number of talks on the liver project (which was performed in Pavia, hence the interest), plus a number of interesting dosimetry techniques, one of which is the Gel dosimeter developed



at Milan University, which was discussed in detail between the Petten and Milan group, as it could be (and became) of great interest to use in the new liver facility at Petten. With respect to the latter topic, Sander Nievaart gave a presentation on the status of the liver project at Petten (September);

- Workshop on "The Requirements for BNCT at a Nuclear Research Reactor": as part of the Enlargement and Integration programme of the JRC, the workshop was held in Prague. Some 40-50 participants attended from New Member States and Candidate Countries, who have interests to develop BNCT in their own countries. The workshop, as well as presenting BNCT and all its aspects, held working group discussions with the participants, where knowledge of BNCT from the experienced BNCT Community (such as Petten) was given and used to develop and (to) write reports on how to develop a BNCT programme in each country. The Workshop was arranged such that on most of the first day, formal presentations on all aspects of BNCT were given by invited speakers, being specialists in the relevant topic. Towards the end of the first day, the workshop participants were divided into 2 working groups: one on "How to build up an irradiation facility for BNCT" and the other on "How to create and organise a BNCT programme". The Workshop ended with a discussion of the final conclusions and on eventual follow-up actions, including the writing of a book with the workshop title as subject (November).

List of peer-reviewed publications

1 Moss, R.L., "The HFR: A Key Research Reactor for Europe", International J. Nuclear Power (Atomwirtschaft), Feb. 2005, 113-116

2 Wittig,A., Moss, R.L., Stecher-Rasmussen, F., Appelman, K., Rassow, J., Roca, A., Sauerwein, W., "Neutron Activation of Patients following Boron Neutron Capture Therapy of brain tumours at the High Flux Reactor (HFR) Petten (EORTC trials 11961 and 11011)", Strahlentherapie und Onkologie, J. Radiation Oncology. Biology.Physics, 12.05, p774-782, 2005

3 Basilico, F., Sauerwein, W., Pozzi, F., Wittig, A., Moss, R., Mauri, P.L., "Analysis of B-10 antitumoral compounds by means of flow-injection into ESI-MS/MS", J.Mass Spectrometry, Vol.40, p1546-1549, 2005.

EUROPEAN NETWORK FOR MEDICAL ISOTOPES AND BEAM RESEARCH – EMIR

Background

The European Network for Medical Radioisotopes and Beam Research (EMIR) Action was initiated in 2001 by the JRC-IE, building on HFR's position in the medical radioisotope production field, to identify and solve difficulties that constrain nuclear medicine and radiotherapy development in Europe and facilitate closer interdisciplinary collaboration. Partners in EMIR include the main European associations of medical radiation specialists, radiopharmaceutical radioisotope producers, nuclear research reactor institutions, research organisations and the JRC.

Work in 2005 focussed on:

- Hosting and organization of the 5th International Conference on Isotopes (5ICI);
- Finalisation and publication of a Survey on the radioisotopes market (analysis of worldwide production capabilities; analysis of demand for therapeutic applications in EU-15 and of guidelines for application of therapeutic treatment; identification of research needs, status and trends).

5ICI

5ICI took place from 24.04.2005 to 29.04.2005. The event was jointly organised by the EC's Institute for Energy (IE) and the European Society for Therapeutic Radiology and Oncology (ESTRO).

Some key figures highlighting the success of the event are as follows:

- A record 315 participants registered to the event; more than 250 attended for the full 5 days of the event;
- 200+ scientific contributions were submitted; the scientific programme involved 6 plenary sessions, 20 parallel sessions, 2 Technical Tours (attracting some 90 participants) and 1 Management Workshop which some 40 people attended;
- A trade exhibition involved 16 exhibitors demonstrated interest and trust in event;
- Decisions were taken during the event's closure to set up an International Council on Isotopes which would be entrusted with the ICI series and promote its convergence with the International Isotopes Society;
- A satisfaction survey was carried out on a sample of 25% of participants; more than 80% were "satisfied" or "very satisfied" with 5ICI.

The 5ICI International Monitoring & Steering Committee has decided to award the hosting of 6ICI to the proposal of the Korean Radioisotope Association (KRIA) which has proposed to host the event in Seoul (South Korea) in 2007. In this frame, a full closure report on 5ICI was prepared and transferred to KRIA shortly after 5ICI.

The proceedings of the conference were gathered and distributed electronically on a CD to all participants at the event. A proceedings book was also published. An electronic copy of the book of proceedings is available on the Publication's page of the website of the Institute for Energy: www.jrc.nl.

Radioisotope survey
The RI Survey, started in end 2003, consisted of four parts: 1- RI production capacity worldwide (extended from the IAEA survey); 2a- European demand for therapeutic RI (extended from the EANM survey); 2b- inventory of medical guidelines for usage of therapeutic RI; 3- status of R&D for medical RI; 4- brachytherapy (BT) data (extended from the ESTRO survey). The report was contracted to an external consulting company (Ariadne Advice & Consultancy) who received punctual support from IE staff.

The Final Report is available on the Publication's page of the website of the Institute for Energy: www.jrc.nl.

MEDICAL RADIOISOTOPE PRODUCTION

Production of radioisotopes
The HFR Petten is one of the most important producers of isotopes for the worldwide medical market and its position of importance will continue to increase. Many important activities of Nuclear Medicine and Radiotherapy specialists worldwide concerning the use of diagnostic and therapeutic isotopes is based upon the sound and reliable performance of the HFR Petten; with it's ca. 280 operating days per year. The direct sales value of isotope irradiations performed at the HFR has increased 55% in the period 2000 – 2005. The most important isotopes are Molybdenum–99, Strontium–89, Iridium–192 and Iodine–125, while a wide range of other isotopes are produced on a routine basis.

In the case of Molybdenium–99 (Mo-99), production capacity has been increased during recent years with the introduction of new in-core irradiation facilities. The Incomodo (2001) and Tycomo (2005) devices both increase the total production capacity of Mo–99 as well as producing larger quantities of Mo-99 from a single irradiation compared to older Mo-99 production facilities. Improved irradiation efficiency also leads to a relative reduction in associated waste.

The closure of the R-2 Reactor at Studsvik has increased the workload demands on the HFR. Within Europe, the planned closure of the FRJ-2 Reactor at Jülich in May 2006 will also place further demands on the HFR.

The features of the general isotope irradiation facilities used in the HFR that allow on-power target changes throughout the Reactor Cycle continues to be of particular importance to the area of Nuclear Medicine, where a wide range of short half-life isotopes are required on an almost daily basis. The regular supply of short half-life isotopes such as Samarium-153, Phosphorus-32 and Rhenium-186 can only provided with these types of facilities supported by the continuous availability of the Hot Cell facilities of NRG. These general isotope irradiation facilities are available to any customer requiring reliable irradiations, performed on a punctual basis.

These facilities are particularly important for the development of new medical products, for the supply of isotopes for new medical developments and to support the early stages of Clinical Trial work using new and novel techniques. In recent years, these services have been a strong feature of the work performed at the HFR. Within NRG, the extension of these services to develop and then routinely provide radiochemicals such as Lutetium–177 is an example of this.

HFR: The Programmes

HFR as a Tool for Fission Reactor Technology

HIGH TEMPERATURE REACTOR IRRADIATIONS IN THE HFR

HTR FUEL IRRADIATIONS

Background
Three irradiation tests of low-enriched uranium fuel types in the HFR were carried out or further prepared to determine their limits with respect to radioactive fission product release with increasing burn-up (enhanced fuel use) and at increased fuel temperature (enhanced efficiency). One such irradiation (HFR-EU1bis) was successfully terminated in October 2005, the next (HFR-EU1) is scheduled to start in early 2006, and a third (HFR-PBMRF1) is planned for start-up towards the end of 2006. 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. 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 string from irradiation to PIE for safety relevant heating tests.

- Irradiation of pebble type fuel produced by NUKEM, Germany at increased temperature, codename *HFR-EU1bis* with simplified fission gas monitoring. Estimated burn-up 15.4% FIMA;
- Irradiation of pebble type fuel produced by NUKEM, Germany and by INET, China, codename *HFR-EU1* with on-line fission gas release monitoring. Target burn-up 21% FIMA for NUKEM pebbles and 16% 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.

Achievements in 2005
The irradiation HFR-EU1bis started in early September 2004 and, despite some technical setbacks, was terminated in October 2005 after 10 reactor cycles thus adding another successful HTR irradiation to the HFR record since the 1970s. At the end of the irradiation (approx. 15.4% FIMA, to be confirmed by PIE), the characteristic release over birth (R/B) fraction was determined as approx. 3.5×10^{-6} which seems to confirm the validity of computational predictions even at this very high temperature, see Figure 17.

For the next two irradiation tests in 2006, the new Sweep Loop Facility for automatic temperature control and on-line fission gas analysis will be used. The installation of this facility in the HFR basement (Figure 18) was finished with hot commissioning expected in early 2006. The Design and Safety documents for both HFR-EU1 and the Sweep

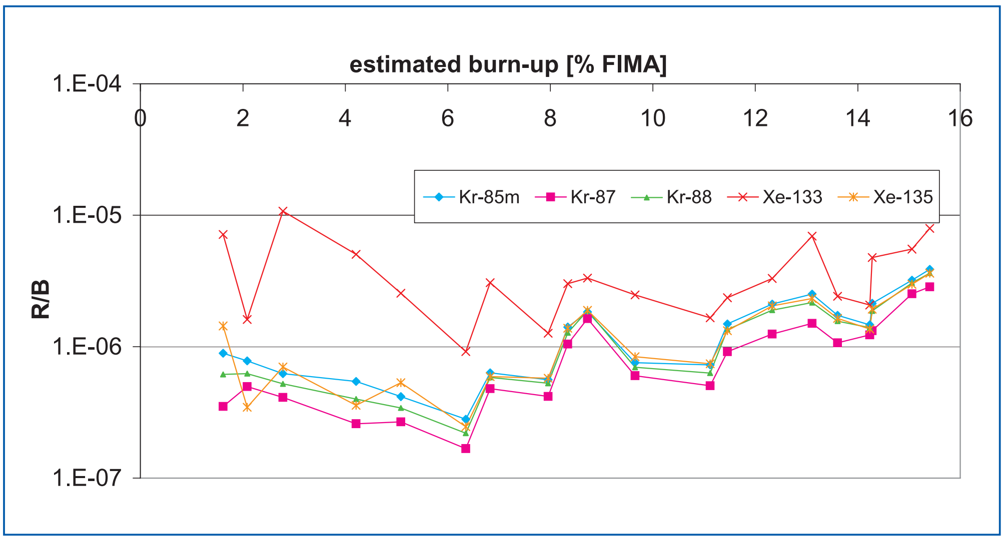


Figure 17 - HFR-EU1bis irradiation - R/B measurements vs. burn-up

Figure 18 - Sweep Loop Facility during cold commissioning in the HFR basement

Loop Facility were approved by the competent HFR safety committees.

In the frame of cooperation with the GIF project "VHTR Fuel and Fuel Cycle", a collaboration agreement with PBMR of South Africa was drafted and technical specifications were fixed concerning the HFR-PBMRF1 irradiation. Nuclear and thermal calculations for design optimization have started. Delivery of the fuel is expected in Autumn 2006, enabling a start-up of the irradiation towards the end of 2006.

In addition, the existing web-enabled database for fuel irradiation data and related documents was upgraded and refined, and was made available to the partners in the concerned FP5 and FP6 projects.

STRUCTURAL MATERIAL OUT-OF-PILE TESTS FOR INNOVATIVE REACTORS

Background

These tests aim at investigating the out-of-pile properties of high-temperature materials to be used in innovative reactors, e.g. as pressure vessel material, control rods or ancillary components. Later on, specimens of candidate materials may be irradiated at conditions typical for their envisaged use. Post-irradiation testing will focus on determining the mechanical properties.

Achievements in 2005

Materials for the conventional part of an HTR power plant were exposed to different chemical conditions and mechanically tested. The suspected negative effect of carburizing/decarburizing on mechanical properties was corroborated for alloys proposed for high temperature helium turbines in a direct cycle power conversion configuration. Low Cycle Fatigue (LCF) tests were performed on typical turbine disc material (Udimet 720, heavily carburized) at 650°C, and the results were compared to uncarburized material. Carburization was shown to have a detrimental effect on the yield strength (typical decrease from 910 to 650 MPa) as well as on LCF performance, in particular as regards the regime of high strain ranges and low numbers of cycles to failure. Such effects may be expected in a reactor due to gas impurities in the primary He coolant.

The need to perform nitriding tests for indirect cycle power conversion components (turbine, heat exchangers exposed to a mixture of 80% N_2 and 20% He) was confirmed and will be done in 2006.

For testing materials for supercritical water reactor conditions, a rig for testing tubular tensile specimens was made operational, and a recirculation loop with a mechanical testing autoclave was delivered with commissioning to full specifications expected in early 2006.

The oncoming years will be devoted to operate these new installations and to test a variety of candidate materials for evaluation.

Figure 19 - Supercritical water recirculation facility for material tests

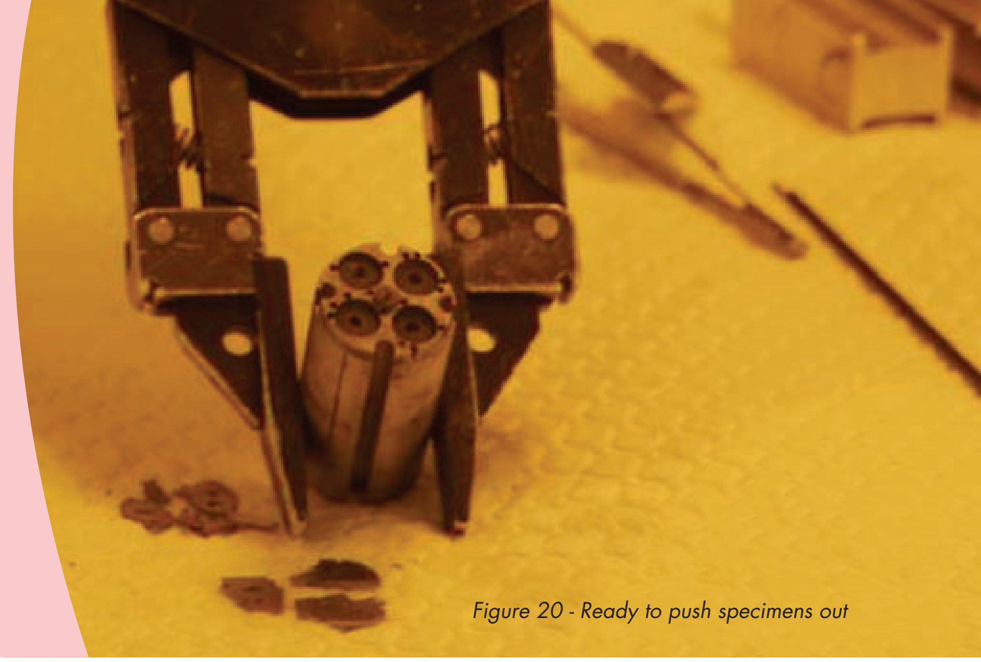


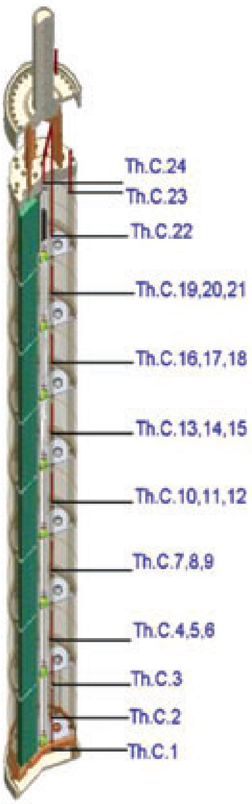
Figure 20 - Ready to push specimens out

HIGH TEMPERATURE REACTOR GRAPHITE IRRADIATIONS

Knowledge of graphite behaviour under irradiation is crucial for the operation of gas-cooled reactors and the development of high temperature reactor technology (HTR/VHTR) and fusion. In the more than four decades of operation, the HFR has contributed strongly to this development through irradiation of graphites, as well as ceramics and composites.

Parts of INNOGRAPH-1A after dismantling prior to unloading the specimens

The facilities at the HFR allow high quality data to be acquired and help provide a vital data platform on which to base future advanced reactor design and developments. In 2005, within the EU HTR project, NRG obtained the first irradiated data on current graphite material, thus ensuring that Europe maintains its lead in this important technological area.



NRG has operated INNOGRAPH-1A irradiation experiment until Spring 2005, achieving the target dose of 8 dpa(graphite) at a nominal temperature of 750°C. The rig contained a number of 200 specimens from 8 different grades of potential candidates for a near future HTR. NRG has developed and installed the necessary post-irradiation test facilities and started a large measurement campaign in 2005.

Post-irradiation measurements performed for INNOGRAPH-1A included linear dimensional change and Young's modulus by ultrasonic time of flight. The volumetric shrinkage behaviour at maximum dose was found to range from 1.5% to 6.3%. Four of the six grades shrank between 4% and 5%. The majority of extended testing like thermal expansion and diffusivity follows in 2006.

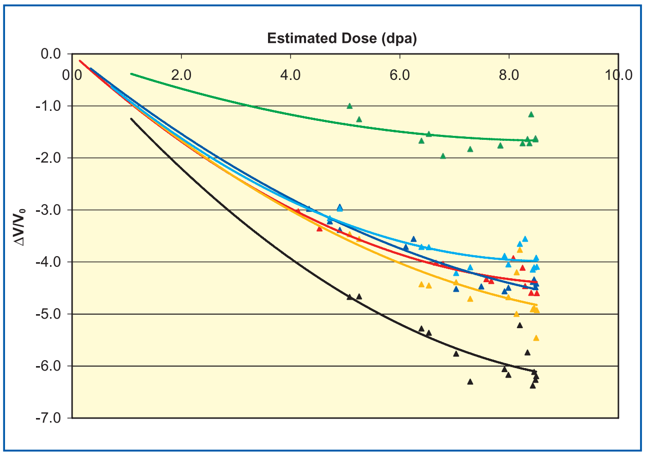
This program forms the basis for expanding the test matrix within the follow-up project RAPHAEL IP. It is foreseen to have part of the loading being re-loaded and continue irradiation to a 3 times larger dose in INNOGRAPH-1B that is to start in 2006. Another high temperature rig, INNOGRAPH-2A, has been designed for irradiation at 900-950°C, which is at the high end of the (V)HTR window. This rig will contain about 150 specimens, and contains newer grades of graphite that became available in 2005.

HTR Vessel Material Irradiation and Post-Irradiation Tests

One of the alternatives considered for HTR is the application of so-called hot-vessel. Modified 9Cr-steels 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.

The irradiation of specimens cut from T91 weldment has been performed early in the year. Longer term post-irradiation creep tests for the FP6 Raphael programme has started. The tests will be performed with target rupture times in the range of 103 to 104 hrs. The first results indicate that the data is close to the RCC minimum rupture stress at 450°C.

Figure 21 - Volumetric shrinkage behaviour of present day graphites irradiated in INNOGRAPH-1A at 750°C to 8 dpa_g.



FUEL IRRADIATIONS FOR THE IMPROVEMENT OF FUEL CYCLES

MICROMOX

Objective

Due to their intrinsic nature, such as their neutronic properties, high burn-ups are technically more difficult to achieve with $(U,Pu)O_2$ MOX fuels than with standard UO_2 fuel elements. This is due to the large amount of fission gas that is produced and released during irradiation with $(U,Pu)O_2$ materials and therefore, the build-up of higher internal pressure in the fuel rods if compared to conventional UO_2 fuels. These higher pressures reduce the experimental margins relatively to safety criteria and lead to a strict burn-up limitation by the safety authorities for this type of fuel. Reduction of gas release or rod internal pressure is however possible by either increasing dramatically the rod free volume, which is actually not compatible with current fuel and reactor designs or, in a more elegant way, by using a new generation of fuels with improved capabilities of gas retention.

The MICROMOX experiment is aimed at studying various MOX fuels with enhanced capability of fission gas retention. More specifically the objective of the project is to study the impact of MOX fuel microstructure on fission gas release at high burn-up and during transient conditions and to compare the performance of various MOX fuels with that of standard UO_2 fuels. In the MICROMOX experiment, eight individual fuel capsules are irradiated in the High Flux Reactor (HFR) in a sample holder designed at the JRC-IE. The target materials are three experimental MOX fuels and one standard UO_2 material. Four capsules are equipped with a central thermocouple and a pressure transducer. Four other capsules are identically loaded but are not instrumented. All the capsules are enclosed in a sodium bath to ensure thermal bonding. The expected burn-up at the end of irradiation is 55-60 MWd/kgHM. The enrichment of the targets was chosen in such a way that such a burn-up will be achieved after two years of irradiation (i.e. 25 HFR irradiation cycles).

Achievements 2005

The first irradiation cycle of MICROMOX, i.e. cycle 2003-10, started on 23rd October 2003 in position H8 of the HFR core. The MICROMOX experiment was loaded in channel 2 of the south-oriented TRIO 131 rig together with the THORIUM-CYCLE experiment, which was previously loaded in channel 1.

Following a reactor scram, which occurred on 13th July 2005, several oscillations/changes were observed in the temperature readings of the MICROMOX experiment. Following, subsequent neutron radiography, taken after the incident (see Figures 1 and 2), this lead to the conclusion that six-out-of-eight fuel capsules and related instrumentation had been displaced over a distance of a few millimeters. The analysis concluded also that the sample holder did not suffer any major damage leading to any concern for both the safety of the experiment and the safe operation of the HFR. As such, continuation of the MICROMOX irradiation was authorised for the whole duration of the experiment in absence of new and unexpected incidental events.

Following a stop of three irradiation cycles, the MICROMOX irradiation was restarted in November 2005 (i.e. cycle 2005-11) and, at the end of 2005, has accumulated 19 out-of the 25 planned irradiation cycles.

Figure 22 - Neutron radiography of the TRIO rig taken during cycle 2005-08 on 7th September 2005 (upper section)

Figure 23 - Neutron radiography of the TRIO rig taken during cycle 2005-08 on 7th September 2005 (middle section)

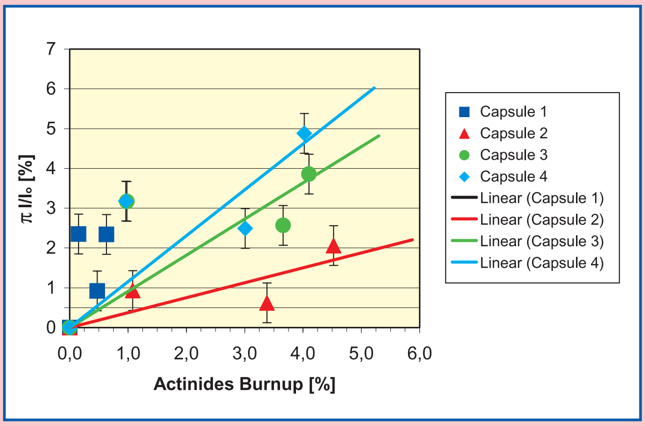


Figure 24 - Estimated fuel stack length elongation as a function of the calculated burnup (the data are based on neutron radiographic measurements) for capsules 1 to 4 (i.e. ThO_2, UO_2, $(U,Pu)O_2$ and $(Th,Pu)O_2$, respectively).

THORIUM-CYCLE

Objective

The use of thorium offers challenging options for nuclear waste reduction, both at the back-end and at the front-end. Thorium, a naturally occurring material, is a fertile material which can be converted into ^{233}U in a nuclear reactor. The subsequent fission of ^{233}U has the advantage that less radiotoxic actinides such as Np, Pu, Am and Cm are produced, when compared to the conventional cycle, where ^{235}U is used as a fuel. An interesting application of the thorium cycle is the once-through thorium-assisted Pu-burning. In $(Th,Pu)O_2$ fuels, the Pu destruction rate can be about two times higher than in $(U,Pu)O_2$ fuels. Since the data for the $(Th,Pu)O_2$ are scarce, irradiation of this fuel type was necessary.
The general objective of the THORIUM-CYCLE experiment is to investigate the behaviour of such type of material up to high burn-up (i.e. higher than 50 GWd/t_{HM}). In the THORIUM-CYCLE irradiation experiment, four target materials have been irradiated in the HFR, namely: ThO_2, UO_2, $(U,Pu)O_2$ and $(Th,Pu)O_2$ (i.e. capsules 1 to 4, respectively). All the capsules were equipped with central thermocouples. As in the MICROMOX experiment, all the capsules are enclosed in a sodium bath to ensure thermal bonding.

Achievements 2005

The target burn-up for the fuel samples was originally >50 GWd/t_{HM}, and the enrichment of the targets was chosen such that that burn-up should have been achieved after 25 HFR cycles (i.e. at the end of 2004). However, in 2005 it appeared that the burn-up achieved was about 10% lower than the planned one. Since the targeted burn-up had not been reached after 25 irradiation cycles, the THORIUM-CYCLE experiment has been further irradiated for three additional irradiation cycles in 2005, starting with cycle 2005-02.
In fact, for the UO_2 target (i.e. capsule 2) the burn-up reached after 25 irradiation cycles was 47.7 GWd/t_{HM} while with three extra cycles of irradiation a burn-up of 52.4 GWd/t_{HM} was reached.

The 28 irradiation cycles (corresponding to a total cumulated irradiation time of 698.52 full power days) of the THORIUM-CYCLE experiment were completed in April 2005 and the irradiated samples successfully transferred to the NRG hot-cells for the planned Post Irradiation Examinations (PIE).

In order to investigate the actual status of the THORIUM-CYCLE experiment, several neutron radiographs were taken at various stages of the irradiation. They were scanned with the high-resolution scanner available at the JRC-IE, analysed with an image analysis software and compared with the X-ray pictures taken before irradiation. In addition, in order to estimate the dimensional changes induced by the irradiation on the various fuels, the neutron radiographs have also been used to assess the fuel stack length at various stages of the irradiation. Based on these measurements, an estimation of the fuel stack length changes as a function of the calculated actinides burn-up has been made and is shown in Figure 24.
It is important to stress the fact that the data shown in Figure 24 indicate a qualitative trend and might eventually represent an upper limit for the linear swelling of the single fuel pellets. The assessment of the actual fuel swelling as a function of the burn-up will only be possible following the destructive post-irradiation examination analyses and may differ from the values shown in Figure 24.

FUEL IRRADIATIONS FOR PARTITIONING AND TRANSMUTATION

The radiotoxicity and long lifetime of radioactive waste components can be reduced by means of neutron irradiation. Due to the flexible experiment design options, the HFR is very well suited for testing of innovative fuel and targets within the area of transmutation of waste. The radioactive waste components that are most relevant for transmutation are plutonium, americium, iodine and technetium, which have all been tested in the HFR.

The transmutation related research is performed within international frameworks. The European network EFFTRA (Experimental Feasibility of Targets for Transmutation) in which JRC-IE, JRC-ITU, CEA, EdF, FZK and NRG participate, has launched experiments for transmutation of americium, technetium and iodine. Within the European framework programme experiments regarding Pu-burning were performed in 2005, and new experiments on Am transmutation were prepared. Innovative designs for Pu-burning were performed in cooperation with European and Japanese partners.

SHIFT

The experiments with americium and plutonium inert matrix fuel were performed in so-called SHIFT sample holders. In this

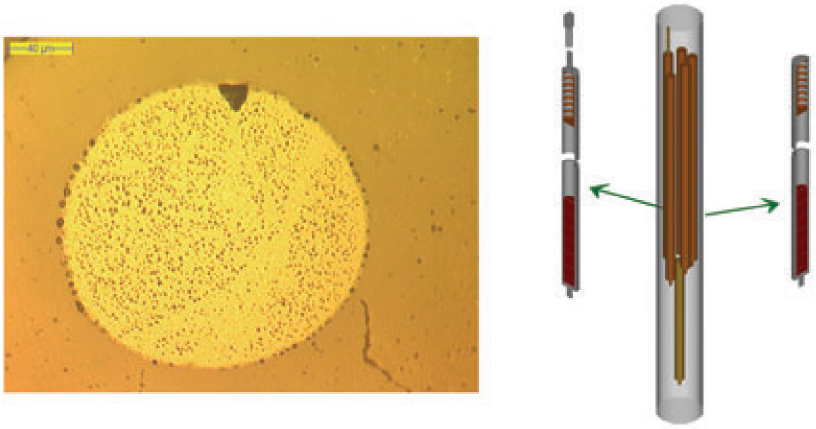


Figure 25 - (left) Cross-section of an irradiated Pu-inert matrix fuel. The picture shows an inert matrix, in which a spherical particle containing plutonium is embedded. (right) A sample holder used for in-core iodine transmutation experiments, showing metal-iodide filled capsules with and without pressure transducers for online pressure monitoring.

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

The experiments with technetium and iodine were performed in an aluminum sample holder which was also placed into an in-core position. A scheme of the in-core facility for iodine transmutation is shown in figure 25. For iodine, experiments were also performed in the pool-side facility, which allows for temperature ramping of the sample. These ramping studies allow to study the behaviour of gas release as a function of temperature.

HELIOS

Objective

The HELIOS irradiation (formerly EFTTRA-T5) was originally planned in the frame of the EFTTRA co-operation to investigate the behaviour of minor actinides and long-lived fission products in the frame of transmutation studies. Currently the HELIOS irradiation is part of a comprehensive Integrated Project (IP) on Partitioning and Transmutation (i.e. the EUROTRANS Project) which has been officially started, as a part of the European 6th Framework Programme, in 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 the microstructure and of the temperature on the gas release and on fuel swelling

Achievements 2005

In close co-operation with the international partners (i.e. CEA, NRG, JRC-ITU and EdF) involved in the project, the test matrix as well as the major design parameters of the irradiation have been agreed.

The test matrix of the HELIOS irradiation will contain both homogeneous, zirconia-based ceramic compounds (capsules 2 and 3) and heterogeneous compounds (capsules 1, 4 and 5), based on MgO and molybdenum as inert matrix. Molybdenum has been enriched in Mo-92 to reduce the production of the long-lived fission product Tc-99 during irradiation. These compounds, i.e. ZrO_2, MgO and Mo-92, have been chosen as most promising matrix compounds for ADS fuel, based on criteria of ease of fabrication, irradiation behaviour and core safety.

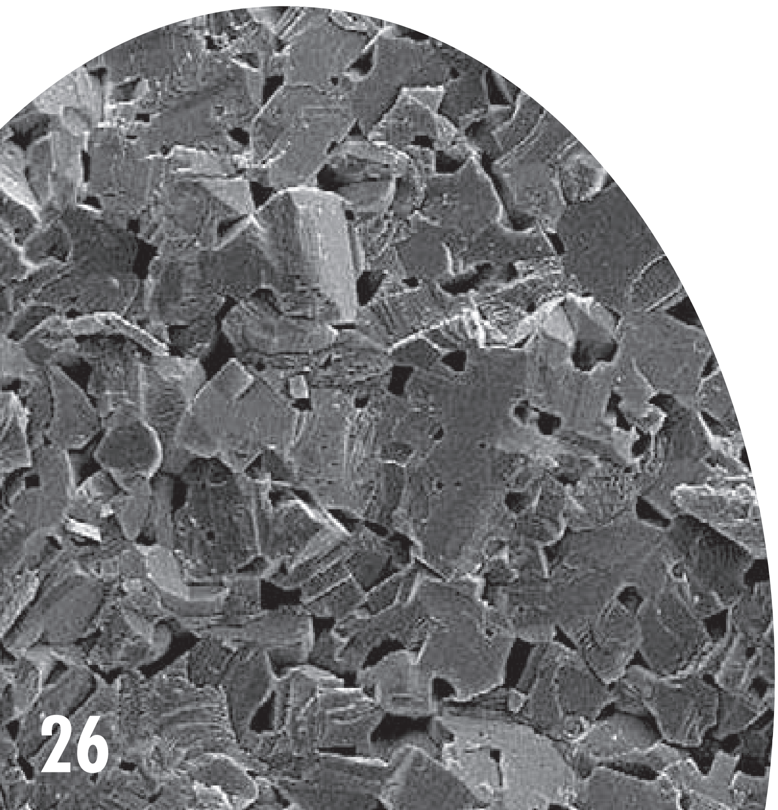


Figure 26 - Microstructure of a MgO pellet for capsule 1 after sintering

To promote helium release from the fuel/target in an early stage of irradiation, two different approaches are followed:

- Provide release paths by creating open porosity, i.e. release paths to the plenum gas. As such, in the HELIOS test matrix, a composite target with a MgO matrix containing a network of open porosity has also been included (capsule 1, as shown in Figure 26);
- Increase target temperature in order to promote the release of helium from the matrix. Two capsules (capsules 2 and 3), with similar composition but with and without plutonium are compared. Due to the absence of plutonium in capsule 2, the fuel temperature of capsule 2 will be much lower than that of capsule 3, thus allowing the study in detail of the impact of the temperature on the helium release.

The total americium concentration in capsules 1-4 will be identical (i.e. 0.7 g/cm^3) in order to enable a comparison of the various fuel concepts. The HELIOS irradiation experiment is planned to be carried out in the HFR core and will last 10 reactor cycles, starting in the first quarter of 2007.

The irradiation duration has been chosen as a compromise to ensure that the central temperature in the $(Pu,Am,Zr,Y)O_2$ pellets are always higher than that of the $(Am,Zr,Y)O_2$ pellets, in order to be able to investigate, during the Post Irradiation Examinations (PIE), the influence of the higher irradiation temperature on the helium release.

TRABANT-02 / SMART

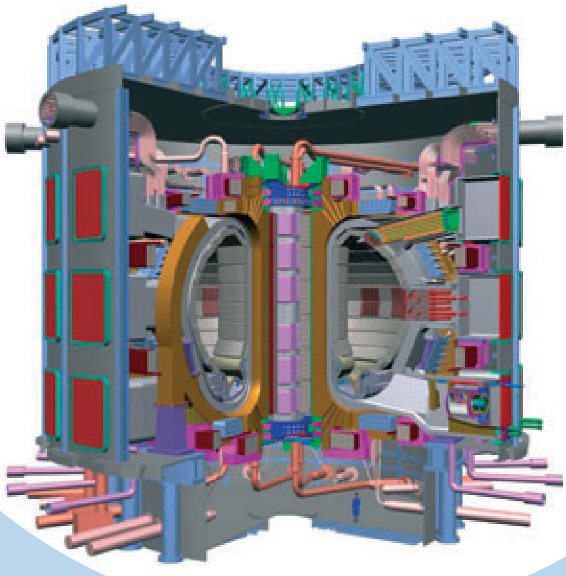
The second phase of the experiment, sponsored by FZK and ITU Karlsruhe, in which two mixed oxide fuel pins with a high Pu (40-45%) content, with the aim to assess the irradiation behaviour of such fuel pins up to medium burn-up, started in HFR cycle 2005-06 for a planned 8-9 cycles irradiation. This second phase also included a third fuel pin, named SMART, composed of 2 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. Due to the history of TRABANT, it was decided to halt the irradiation after one cycle to take a neutron radiograph to observe any untoward behaviour. It was indeed observed that both TRABANT fuel pins had experienced substantial melting, but no breach of cladding. Nevertheless, it was decided that these 2 fuel pins should no longer be irradiated. The third fuel pin (SMART) would continue. Consequently, new nuclear calculations and a revised Design and Safety Report are necessary prior to continuation. The re-start is scheduled for 2006.

OTHER TRANSMUTATION WORK

Neutron Transmutation Doping of Silicon

Silicon is used as the basic material in the semi-conductor industry. When it is doped with a small concentration of other atoms, e.g. boron or phosphorous, the silicon acquires optimum semi conductor characteristics. In most cases, the dosed atoms are inserted into the silicon during the production of the silicon ingots. A very homogeneous doping of phosphorous in the silicon ingot can be induced by irradiation of the ingots in a nuclear reactor, which causes the transformation of ^{30}Si into ^{31}P. This neutron transmutation doped silicon has a very homogenous electrical resistance and is therefore very suitable for power electronics.

In 2005, a silicon doping facility was in operation in the HFR and to meet growing demand, another facility is under construction. The facility in operation is a facility for ingots with an outer diameter of 101.6 mm (4 inches) and a maximum length of 500 mm. The new facility will be suitable for ingots with an outer diameter of 5 and 6 inches.



HFR: The Programmes

HFR as a Tool for Fusion Reactor Technology

ITER AND LONG-TERM FUSION MATERIALS DEVELOPMENT PROGRAMME

Efforts into the development of electricity generation from fusion started in the middle of the last century and aims at achieving industrial production of energy from fusion power plants by the middle of the 21st century. Following the achievement of the Joint European Torus (JET) experiment that produced tens of MW of power during a few seconds, which is already two orders of magnitude larger than that achieved in the tokamak experiments a decade before, the next step is ITER. The ITER fusion reactor will use deuterium and tritium as fuel, and is designed to produce 500 MW thermal power during pulses lasting at least 1000 seconds. The initiative to build the ITER was finally agreed in 2005. Representatives of the European Union, Japan, the Russian Federation, USA, China and South-Korea reached agreement to construct ITER at the site of CEA Cadarache in southern France. Later, India joined the project consortium as well. ITER is currently planned to start operation in 2016.

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

ITER vessel/in-vessel

It is anticipated that the segments of the vacuum vessel wall of ITER may have to be repaired or port extensions may need to be replaced. The reweldability investigations at NRG were extended to ITER-relevant radiation regimes and candidate welding techniques (such as NarrowGap TIG, EB, Hybrid/laser). This activity should enable to design cost-effectively experimental campaigns involving neutron irradiation of thick section stainless steel. In 2005 a new set-up for instrumented weld trials was developed, that allows to compare different welding processes, and validation of numerical simulations of the welding processes in unirradiated steel. This will form the basis for further work with irradiated weld coupons. Some welding trials were performed on 0.01 dpa irradiated ITER grade stainless steel.

In one of the European design concepts, the ITER first wall panels are attached to the blanket modules by bolts. NRG investigated the stress relaxation behaviour under neutron irradiation of two candidate materials: Alloy 625+ and PH13-8Mo. This involved a series of three irradiation rigs with pre-stressed nut-and-bolt assemblies, bent strips and fatigue specimens. Of the two candidates, the PH13-8Mo shows less stress relaxation and strength capabilities that are more suitable for the engineering design. The irradiated Alloy 625+ fatigue specimens were tested in an elastic, high cycle fatigue mode. This material shows significant irradiation softening, which affects the fatigue behaviour at higher doses. It allows lower stress levels to be applied than those possible for the unirradiated material.

A new irradiation campaign is being prepared 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 will be of the proven SUMO type, modified to have two temperature zone, at 200 and 300°C.

NRG assisted the ITER Central Team in preparing the ITER Materials Properties Handbook (MPH). This comprises a.o. reviewing and assessing irradiation effects in Alloy 718 and ITER grade 316L(N) stainless steel.

SPICE (Fusion)

The irradiation project SPICE has been carried out in the frame of the European Long-term Fusion Materials Development Programme. The objectives are to evaluate the mechanical properties of Eurofer 97 samples after irradiation at doses of 15 dpa and at different irradiation temperatures (250/300/350/400/450°C). The material was prepared and characterised by the Forschungszentrum Karlsruhe (FZK), Germany. The instrumented sample holder contained 180 mini charpy, 91 tensile and 160 fatigue specimens. The irradiation started in 2001 and was completed in May 2004. In 2005 the rigs were dismantled at the NRG Hot Cell Laboratories and the specimens were sent to FZK where they have been tested. The dosimetry was carried out by the neutron dosimetry group of NRG.

Helium cooled pebble bed sub-module operation

The fuelling of the first generation power plants will be based on the fusion of deuterium and tritium. The latter has to be produced by transmutation of lithium through the plasma generated neutrons. Present blanket designs consider solid as well as liquid lithium compounds, combined with a neu-

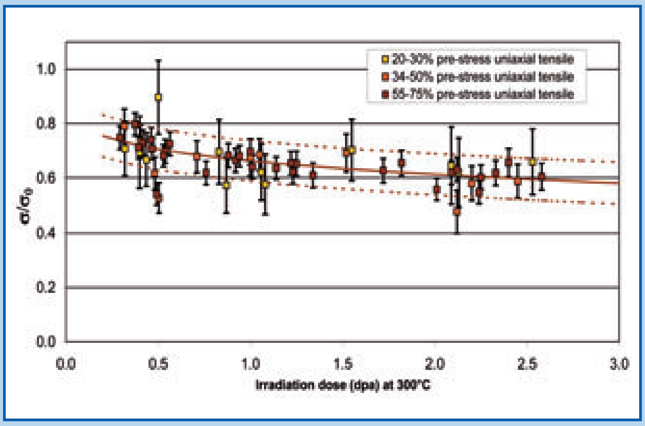


Figure 27 - Stress relaxation trend line for PH13-8Mo martensitic steel

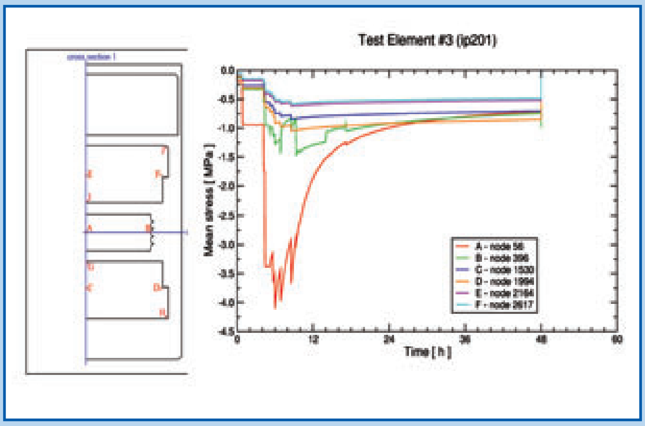
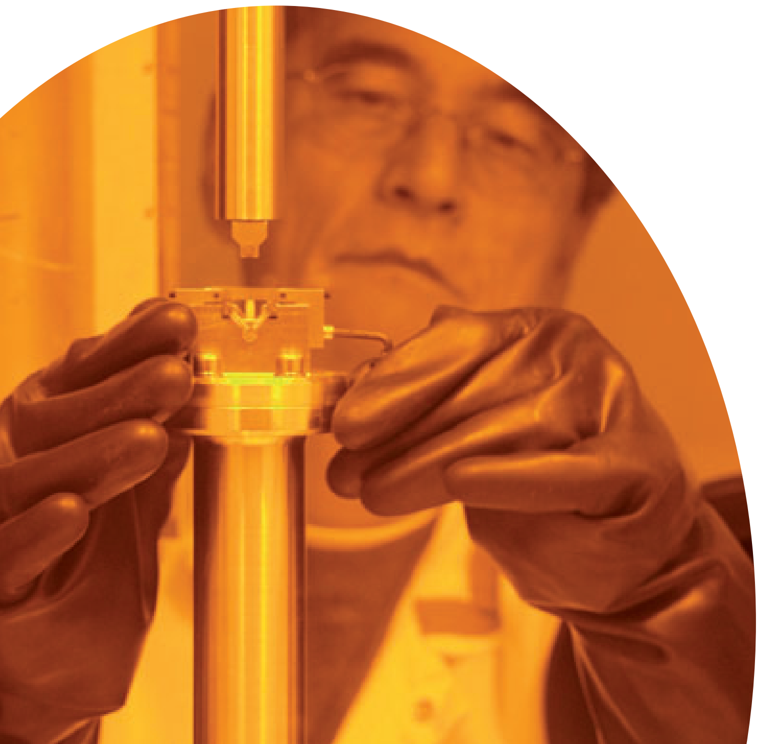


Figure 28 - Reconstruction of the evolution of mean stresses in the PBA breeder bed #3 at first start-up of in-pile operation on HFR

tron 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 needs closely to follow the design of blankets for DEMO and fusion power plants. It is essential to be able 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, closely following the major design for ITERs intended TBMs, were tested during 2003 and 2004 in the HFR. This irradiation campaign provides experimental data to verify and validate models used for predicting TBM behaviour. On-line process readings of temperatures, pressures and tritium production allowed detailed evaluation. Tests prior to irradiation contributed to understanding the thermo-mechanical behaviour of pebble bed assemblies. The experiment has already resulted in improvement of the nuclear and thermo-mechanical analyses. Dismantling of the rig started in 2005, allowing detailed post-irradiation examinations to be done in 2006. The P.I.E. is to confirm possible evidence of gap formation at pebble-bed wall interfaces. In addition a wealth of information can be gathered on material compatibility and TBM relevant instrumentation issues.



Functional fusion blanket materials

In the frame of the EXOTIC (EXtraction Of Tritium In Ceramics) series, a new irradiation started with meta-titanate pebbles from CEA (F). This experiment, EXOTIC-9, focuses on the in-pile tritium release characteristics. First results showed significant inventory build-up, as expected from the porosity characteristics, with a large fraction of closed porosity.

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. Conflicting requirements and design complexity have given difficulties in consolidating a finalised design, prior to the HEU-LEU conversion of the HFR. Extensive pre-testing and X-Ray tomography of pebble stacks before irradiation is applied to improve the quality of the results expected from post-irradiation testing. The test matrix and sample selection were slightly modified to accommodate advanced pebble productions: FZK (Germany) and CEA (France) provided additional specimens. Further neutronics validations are performed being to allow rig manufacturing and assembly in early 2006. Japan and USA are partners in the frame of the IEA (International Energy Agency) implementing agreement on Nuclear Technology.

Two high dose irradiations of beryllium specimens, HIDOBE-01 & 02, started in the second quarter of 2005. The HIDOBE project objective is to quantify the long-term behaviour of Be in terms of swelling, creep and tritium retention and validate preliminary model descriptions. Beryllium pebble stacks will be irradiated in the HFR for a four-year period. In the frame of the IEA implementing agreement on Radiation Damage Effects in Fusion Materials, partners in the EU, Japan and the Russian Federation have provided different grades of beryllium specimens.

In the area of lithium-lead based blanket concepts, new designs were made based on the successful series of LIBRETTO. Two rigs have been designed and manufactured to allow monitoring of in-pile tritium release and obtain insight into permeation characteristics of Eurofer tubes under relevant irradiation parameters, at nominal 350°C and 550°C regions respectively. The Tritium Measurement Station (TMS) is being used to monitor and control the experiment. Both the first and second containment are swept with a He + 1000 ppm H_2 gas flow for tritium extraction. This allows direct comparison of tritium production and permeation.

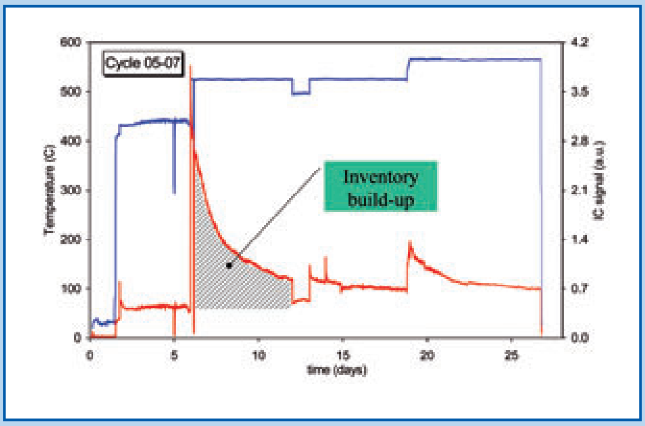


Figure 29 - Tritium release rate and temperature evolution for meta-titanate pebbles irradiated in EXOTIC-9/1

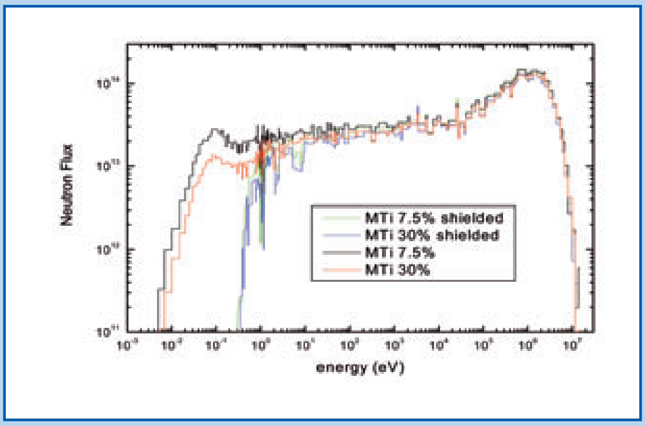


Figure 30 - Example of neutron flux spectra in HICU calculated for various ^{6}Li contents

In-situ oxidation and tritium permeation

Coatings are being investigated which will serve to improve corrosion resistance of Eurofer in lithium-lead and reduce tritium permeation rates into the helium coolant circuit. It was finally decided to apply an in-situ oxidation process, as it would enable a more direct determination of the integrity and permeation properties of the steel's oxide layer. Detailed analyses are planned for 2006.

Structural steel for ITER test blankets

Austenitic stainless steel is widely used in fission reactor components. The specific fusion environmental conditions make such steels less attractive because of their high swelling rates and helium embrittlement properties (1). Conversely, with a micro-structure that prevents high swelling rates and helium embrittlement, ferritic martensitic steels have become the reference structural steel for blankets. Another advantage of such steels is that, providing the impurity level of trace elements can be controlled, they can be made with alloying elements that allow re-processing after less than 100 years after shutdown. The manufacture of such alloys has been successfully demonstrated by the Japanese and EU steel industries. This class of steels is called Reduced Activation Ferritic Martensitic (RAFM) steel. A whole set of irradiation projects with post-irradiation testing is necessary to qualify such 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 on RAFM steels up to 15 dpa. Extensive post-irradiation testing is ongoing at NRG's Hot Cell Laboratories, including fracture mechanics tests and creep-fatigue interaction tests in low cycle fatigue and fatigue crack propagation.

The SUMO-09 capsule irradiation with three temperature levels (250-300-350°C) was completed at nominal a 2.5 dpa. The post-irradiation testing involves small size fracture specimens and exploration of crack-propagation in sandwich systems with compliant layers.

The irradiation stress relaxation experiments STROBO-06 and -07 started in the last quarter of 2005. 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 designed for three temperature levels (300-450-500°C).

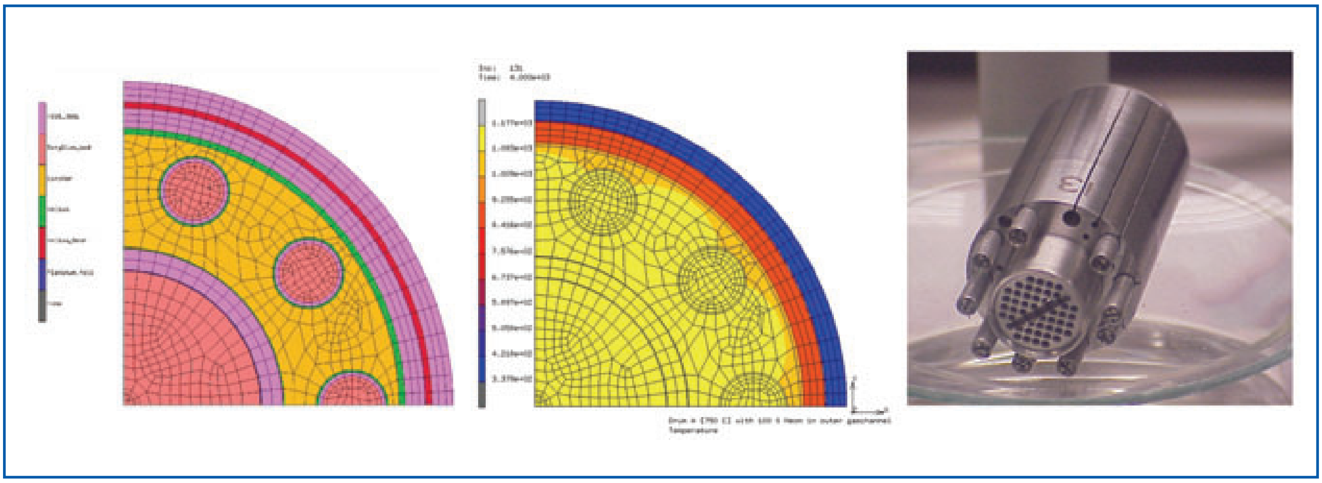


Figure 31 - Thermal analysis of a drum loaded with an 11 mm beryllium bed in the centre and small pebble stacks around, and a loaded drum

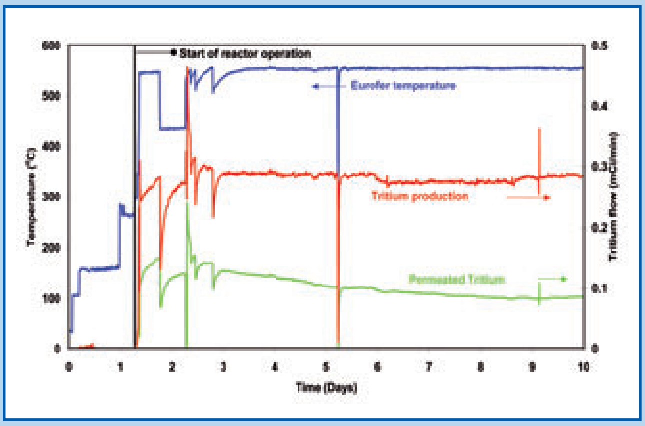


Figure 34a - In-pile data from the 1st irradiation cycle of LIBRETTO 4/1

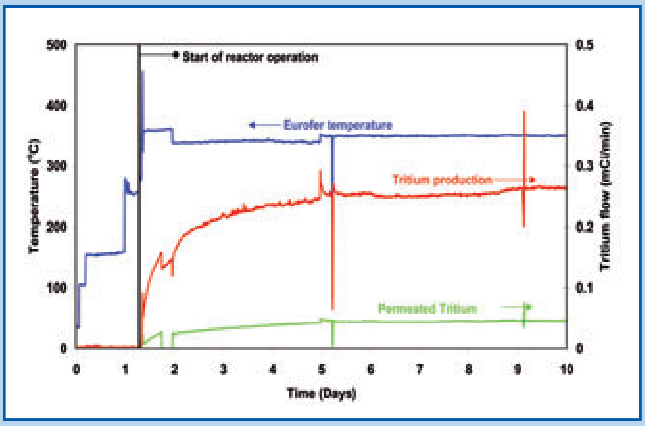


Figure 34b - In-pile data from the 1st irradiation cycle of LIBRETTO 4/2

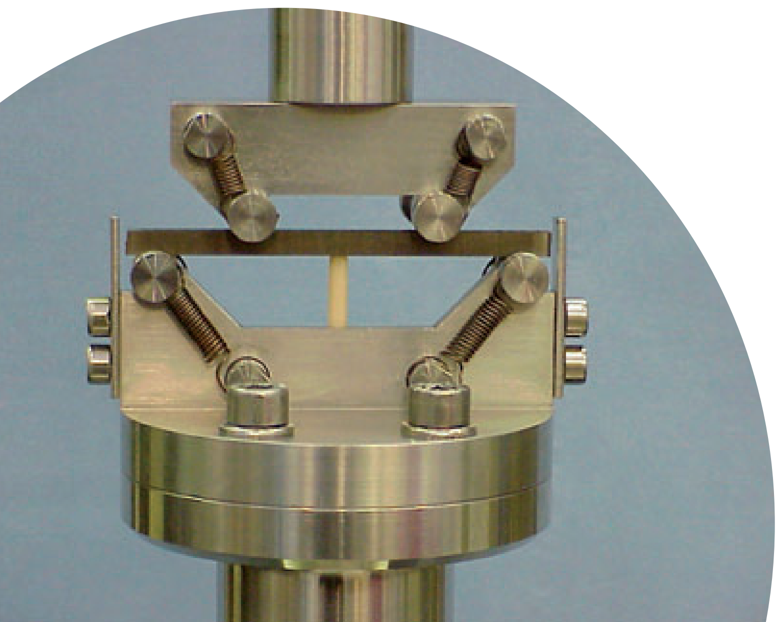
Silicon carbide ceramic structural material

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 may 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 that allow for such operating temperatures. Silicon carbide ceramic composite is a candidate material, which present attractive strength properties up to 1000°C, but also displays some drawbacks that need to be eliminated:

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

The earlier SICCROWD irradiation at 600°C up to 950°C and subsequent post–irradiation examinations methodology formed the basis for a follow-up project with new 2D and 3D composites. This involves 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 SiC/SiC. A hybrid blanket design using steel girders with parts largely made from silicon carbide may be the nearest application of such material in fusion power development.

Figure 32 - Bending configuration and specimen design



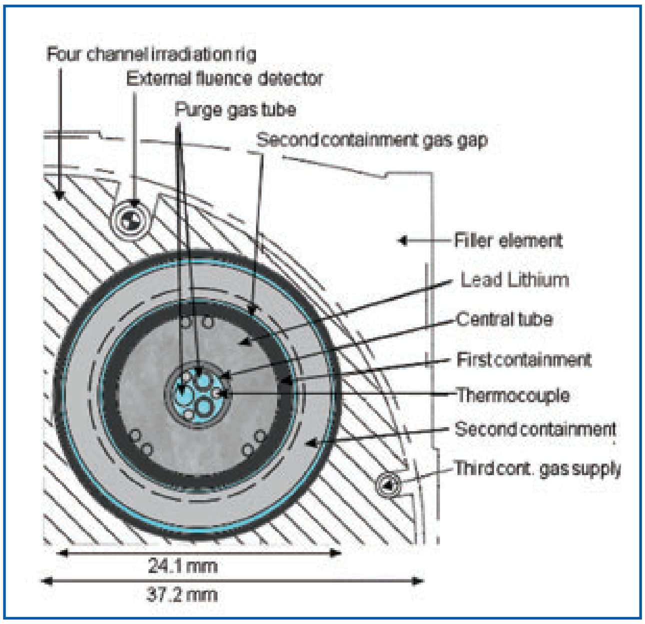


Figure 33 - Radial cross section of one LIBRETTO 4 experiment

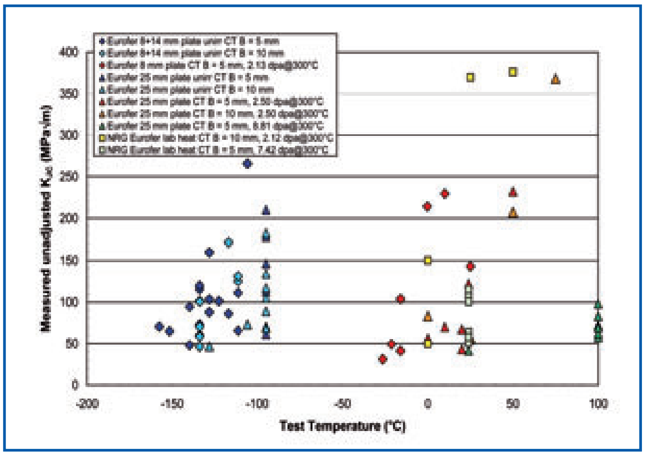
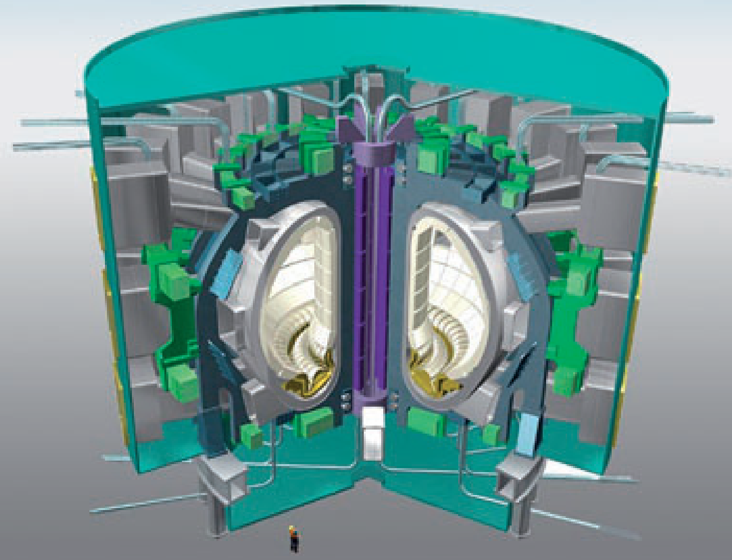


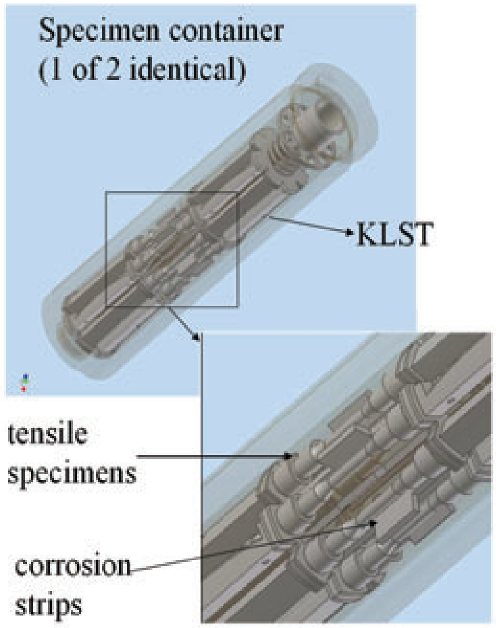
Figure 35 - Fracture toughness test results on unirradiated and 300°C irradiated Eurofer97 plate materials, all W = 22.5 mm



ADS MATERIAL DEVELOPMENT

Objectives
In Europe an Experimental Accelerator Driven System (ADS) for the transmutation of Actinides is being developed, which uses liquid Lead Bismuth Eutectic (LBE) both as reactor coolant and spallation neutron source. LBE has a low melting point (135°C), but may corrode structural materials and welds. In addition, transmutation of Bi to the highly radiotoxic ^{210}Po is a safety issue in the design of the ADS. Materials R&D is needed to test the corrosion behaviour of T91, 316L and weld specimens during irradiation in contact with LBE and to examine after irradiation the deposition of ^{210}Po in the containers and on the specimens.

Achievements in 2005
As LBE expands after solidification, it was necessary to develop a special thick-walled design to withstand the stresses from solidified LBE after filling and in between irradiation cycles of the HFR. The two containers will be filled with specimens, kept in place by separation plates for the different levels of loading for each capsule. Special attention has been given to the connectivity with the LBE filling station at SCK-CEN at Mol, Belgium, where the containers will be filled in 2006. The sample holder and containers are designed for operation in a peripheral in-core position of the HFR, and a target dose of 2 dpa.



HFR: The Programmes

HFR as a Tool for Research

NEUTRON BEAM RESEARCH

In 2005 the HFR Unit has undertaken significant efforts to upgrade and revitalize the neutron beam facilities at the High Flux Reactor. In fact, work has been performed on instruments at five different beam lines and in all cases significant progress has been made. Three instruments, the NEU-DI-CIWI facility at HB4, the SANS facility at HB3b and the Neutron Radiography facility at HB8, have actually been brought to operational state in the course of the year.

As a consequence of these upgrading and renovation activities, the facilities were actually not available for experimental investigations for most of the year. Therefore only two measurement campaigns for estimation of residual stresses have actually been performed in the context of NET related activities.

The NEU-DI-CIWI facility at beam tube HB4

The NEU-DI-CIWI facility has been installed in place of the Large Component Neutron Diffraction Facility in front of beam tube HB4 (Figure 36). This facility is dedicated to residual stress analysis in irradiated components relevant to nuclear power applications, and its dominant feature therefore is 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. The central element of this facility is a transport and experiment container, which provides the equivalent of 15 cm lead shielding and is used both for transport of the specimens between the HFR and the Hot Cell Facilities and for holding the specimens during the experiments. Inside of the container there is a small positioning table providing 100 mm of linear movement in the x-, y- and z-directions and about 135° of specimen rotation about a vertical axis. In addition to the container, lead shielding has been installed around the incoming and diffracted neutron beams. A Bi-single crystal of 9 cm thickness is available to protect the neutron detector in case the radioactivity of the specimens would prevent it from functioning properly. The entire set-up has been completed in 2005, but only test experiments on non-irradiated samples could be performed during the year.

It is foreseen that after completion of measurements in the irradiated steel specimens the NEU-DI-CIWI facility will be disassembled again and the Large Component Neutron Diffraction Facility will be put back in its place. Both facilities in the future could 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.

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

In 2005, a new floor was installed in front of beam tube HB5. The neutron scattering terminology for such a floor is "Tanzboden", which is the German word for dance floor. It is essentially a granite floor that has been laid with high precision. On such a floor high precision movements of neutron scattering instrumentation are possible using so-called air pads and the floor also facilitates easy re-positioning of the entire instrumentation, which may weigh more than 1000 kg, with high precision. At the end of the year the new diffractometer was delivered to the HFR (Figure 37). This new instrument allows for handling of much larger specimens in a much more flexible way. The specifications for the new instrument control software have been prepared in 2005, and the new facility is expected to be in operation by Spring 2006.

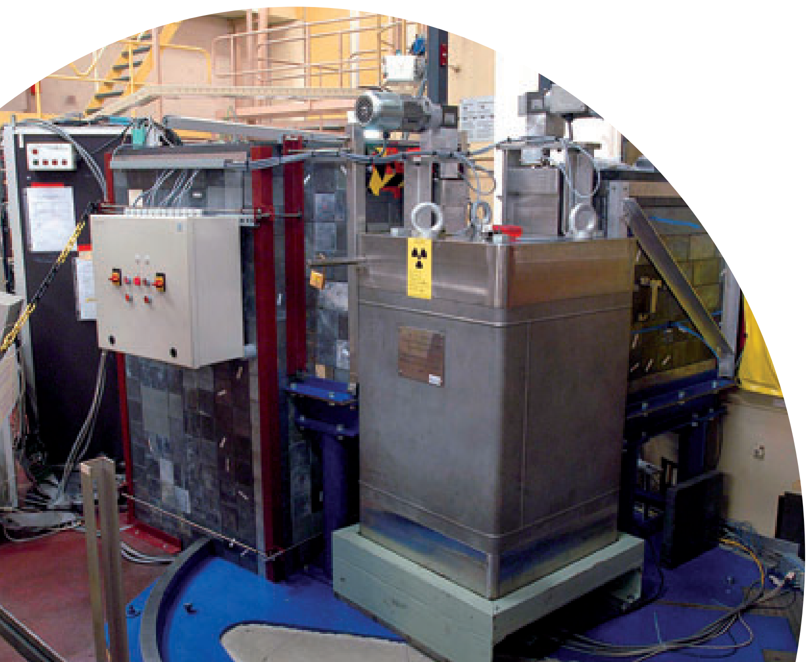


Figure 36 - HFR/HB4 experimental set-up, using the NEU-DI-CIWI facility, for residual stress analysis in irradiated weld specimens based on neutron diffraction

Figure 37 - HFR/HB5: new diffractometer for residual stress analysis installed on "Tanzboden" floor

The Neutron Radiography Facility at beam tube HB8

The HB8 Neutron Radiography (NR) facility produces images of components and structures on film, using neutrons as the penetrating irradiation.

The NR-facility is installed at the horizontal HFR beam tube number 8. The facility consists of the following major components:

- an in-pile collimator with a rotating inlet diaphragm of 10 and 34 mm diameter;
- a beam shutter;
- a filtering system with switchable filters (mono-crystalline Si and Bi, and polycrystalline Be). The Be and Bi filters are situated in closed cycle cryostats with helium expanders and vacuum containment. A fourth filter could be placed in an empty filter position if required;
- a central shielding block which accommodates the filter station and the imaging camera when performing inspections on radioactive fuel rods, or provides collimation to the flight tube and imaging station when employed for inspection of non-radioactive objects;
- a telescopic flight tube, which allows to position the imaging station at 9 or 11 m from the HFR core;
- an imaging station and an instrumentation console for the operation and control of the facility and the neutron beam.

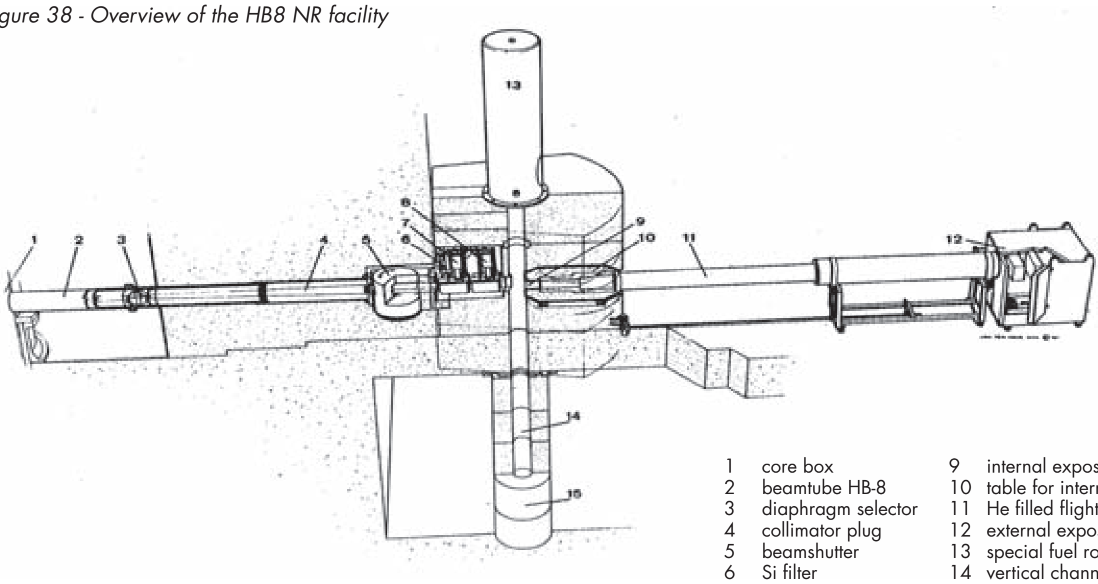
The HB8 NR facility can be used for both:

- inspection of radioactive fuel rods of up to 4 m length;
- inspection of non-radioactive materials and structures using various beams of different neutron energies:
  - sub-thermal neutron beam (with neutrons of approx. 80K, E > 5 meV);
  - filtered thermal beam (with a low gamma radiation component);
  - thermal beam.

The various neutron beam types are easily interchangeable and the facility characteristics are of a high quality, e.g. high collimation ratio, L/D. The HR8 NR facility is particular very suitable for studies related to new applications in NR.

A schematic representation of the facility is shown in Figure 38. The properties of the facility are summarised in Table 4.

Figure 38 - Overview of the HB8 NR facility



1	core box	9	internal exposure station
2	beamtube HB-8	10	table for internal camera
3	diaphragm selector	11	He filled flight tube
4	collimator plug	12	external exposure station
5	beamshutter	13	special fuel rod container
6	Si filter	14	vertical channel for fuel rack
7	Be filter, 50K	15	shielding column
8	Bi filter, 50K		

Figure 39 - Refurbishment of HB8

FLIGHT TUBE LENGTH		9 M	11 M
Neutron fluence rate at object plane ($m^{-2}s^{-1}$)	Subthermal filter Be & Bi	$1.6*10_9$	
	Pure thermal filter Si & Bi	$4.2*10_9$	$2.5*10_9$
NR camera characteristics	L/D ratio	150 (sub thermal) 540 (thermal)	750
	Cd ratio	560 (sub thermal) 547 (thermal)	667
Beam dimensions at object plane		220 mm diameter	250 mm diameter

Table 4 - Characteristics of the NR facility for non-radioactive components

Current situation
Prior to 2005, the installation had been out of commission for several years. In 2004, a decision was taken to re-commission the facility. During 2005, the helium compressor and helium expanders of the cryogenic cooling system and the beryllium filter and bismuth filter have been renewed, see Figure 39.

The vacuum oil diffusion unit has been replaced by a Turbo pump stand. Cryogenic temperatures are now measured with new Pt-100 Platinum thermo-elements, new vacuum-sensors and new vacuum readouts. The thermal contact of the element-tips on the filters is now improved and the indium sealing of the vacuum-containment has been replaced. The neutron telescopic flight tube has been fitted with new sealing to enclose better the helium gas inside.

The instrumentation in the 19" rack has been restructured with a hybrid recorder for analogue recording of temperature and pressure. A dedicated toolbox has been purchased and is available for the facility.

The commissioning of the facility was successfully executed and a series of test exposures were made. The results are of an exceptional quality, see fig 40.

Radioprotection
Dose rate measurements were performed with test samples in the imaging station with all possible filter combinations and diaphragms. The neutron-shielding was sufficient and neutron dose rates are of a tolerable value. The amount of gamma radiation in the vicinity of the station, produced by the objects in the imaging station, was however above levels. This resulted in the placement of a 5 cm lead wall, which brought dose rate down by a factor of 10. A new imaging station will be ordered to accommodate these dose rate values.

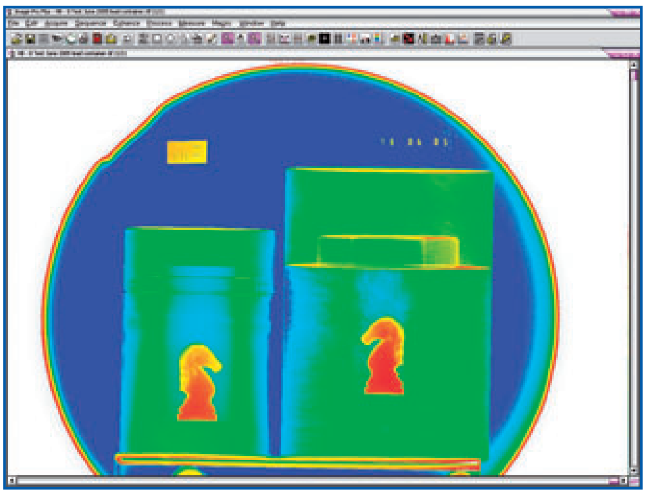
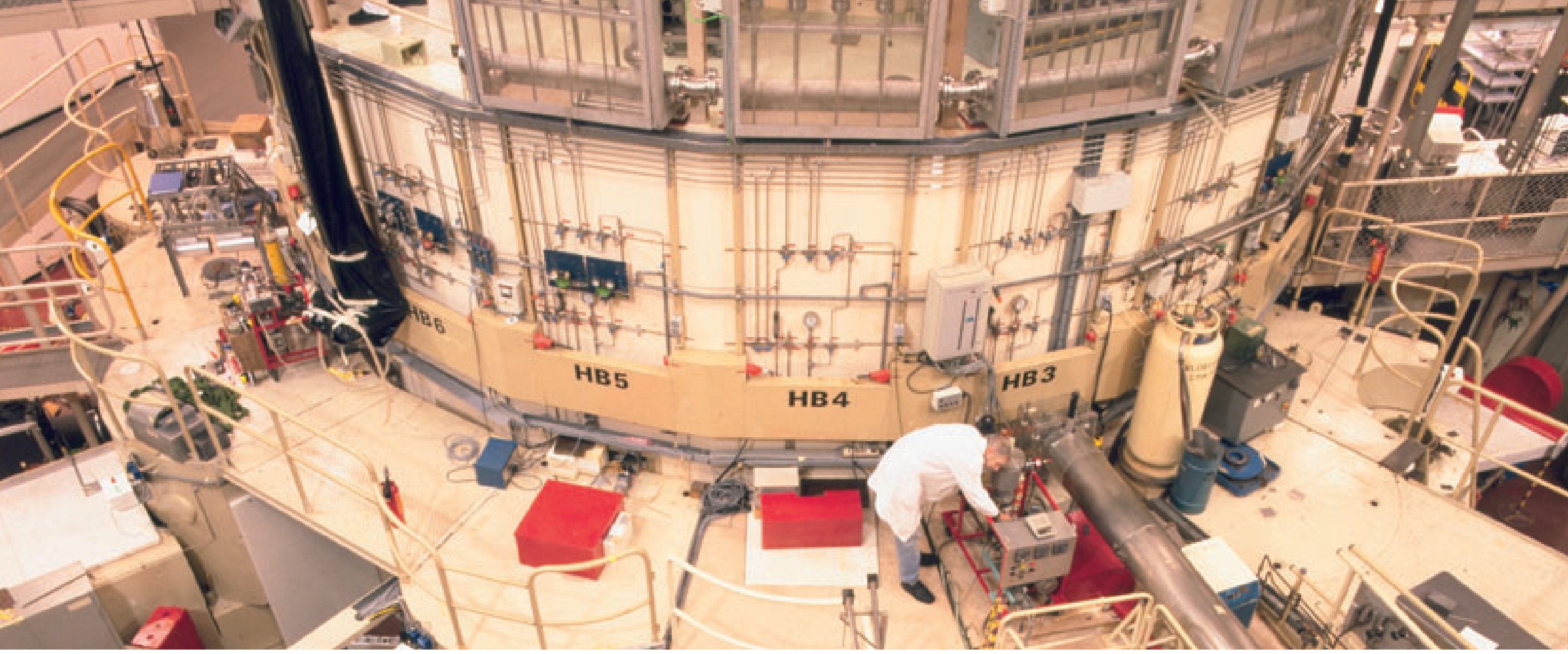


Figure 40 - Image (example) of Chess pieces in Lead Containers



Development of the Small Angle Neutron Scattering Facilities at the HFR

Small-Angle Neutron Scattering (SANS) is a technique used for characterizing sizes (size distributions) and shapes of inhomogeneities in materials and in some cases their mutual interactions. Applications in material science include: phase stability of alloys; interface studies; grain boundary studies; nucleation and growth of precipitates of alloys; characterization of distributed damage in metals and ceramics subjected to creep, fatigue, microstructural changes after heat treatment; porosity of materials; nanocrystalline materials and influence of grain size; non-magnetic materials; in-situ densification of ceramics; segregation processes; and voids & defects. SANS is currently emerging as a powerful non-destructive method for the investigation of irradiation and thermal ageing induced damage in steel alloy weld materials.

The main characteristics of the current HFR/SANS facility are 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 HFR/SANS facility has a range of accessible **Q** values between 5 x 10^{-3} and 0.4 $Å^{-1}$. 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 HFR SANS facility is roughly 1-100 nm.

However, the neutron flux at HFR/SANS is ca. 10^4 n $cm^{-2}s^{-1}$, and based on the proposed upgrade it is expected to be in the range of 10^6 n $cm^{-2}s^{-1}$, is available at most state-of-the-art facilities in Europe. In addition, the envisaged upgrade will give access to the desired range of long wavelengths, i.e., 5 to 20 Å.

This upgrade in the performance 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 will result in a unique and autonomous Combined HFR Laboratory for the characterisation of RPV welded internals within Europe.

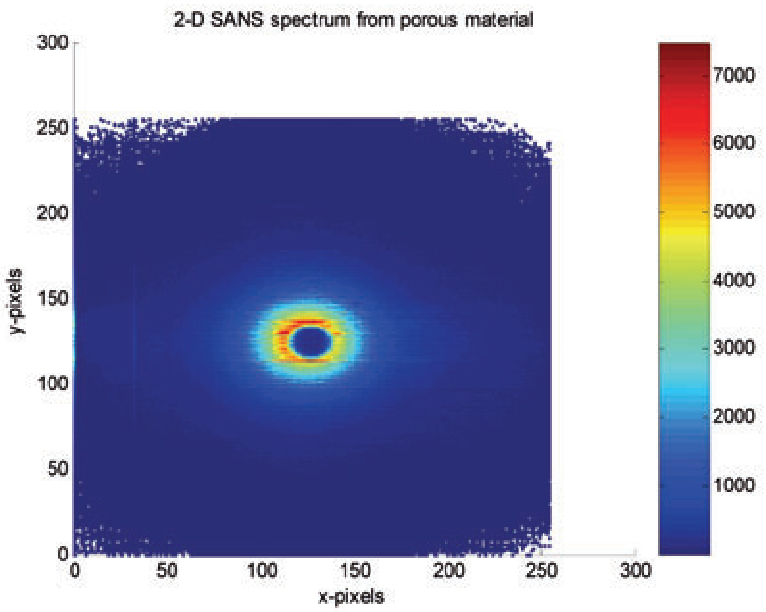
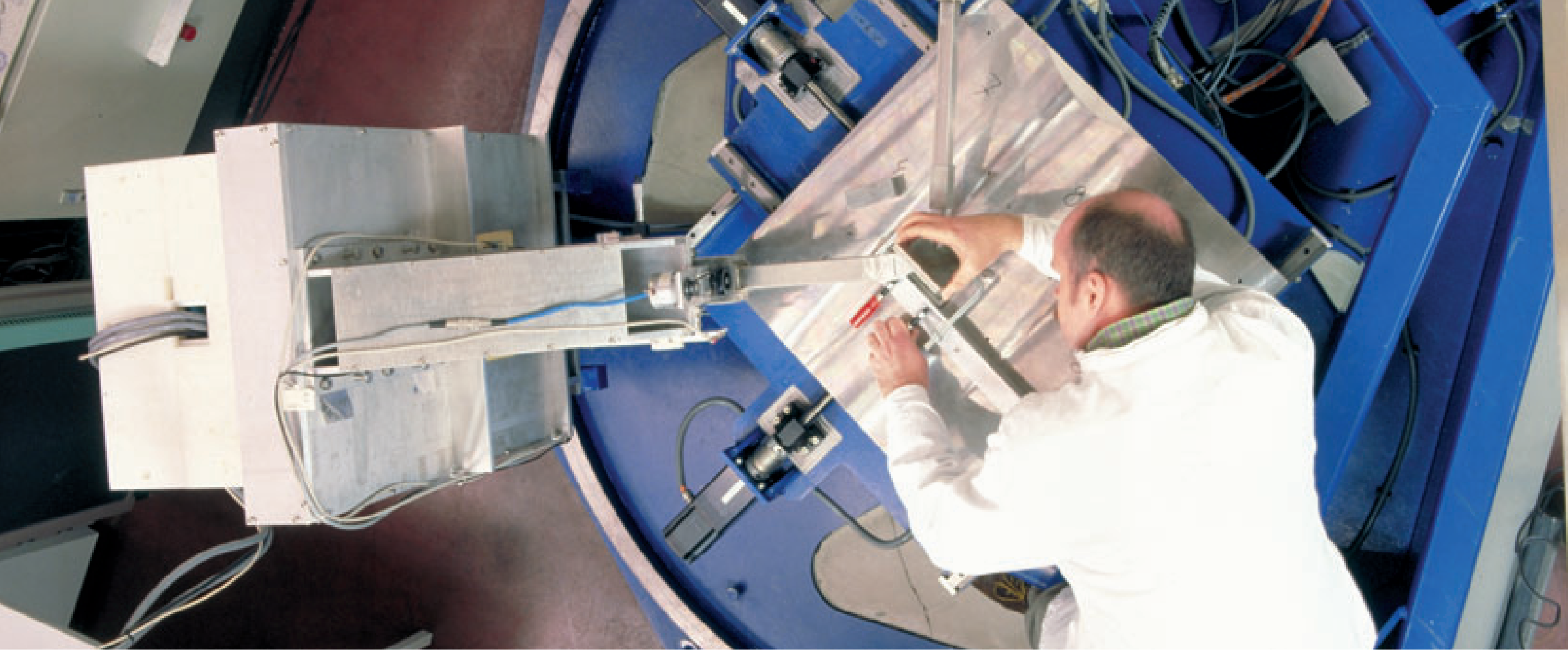


Figure 41 - Neutron spectrum obtained from porous material using the 2-dimensional SANS detector in its current set-up. The beam shutter is clearly visible in the middle where the neutron count is very low. The legend is in neutron counts. Analysis shows that the detected pore size is ca. 70 Å

Re-commissioning of the current SANS facility at HB3b

The HFR Small Angle Neutron Scattering (SANS) facility has been developed and built in the late 80's – early 90's in the context of the then ECN research activities on solid state physics. At present, re-commissioning of the SANS facility is underway. After having been idle for some 10 years, some of the equipment at the facility was found to be obsolete; other parts were simply not functioning anymore. A lot of the obsolete equipment has been replaced in 2005, and replacement for non-operational equipment has been ordered. New software has been installed for detector and sample motion control. In fact, at the end of 2005 it has been possible again to collect scattering signals from samples placed in the neutron beam (Figure 41). In view of the shortcomings of the existing HFR-SANS facility at beam tube HB3b, JRC has decided to embark on the development of a completely new facility at beam tube HB10, which will involve a dedicated building outside of the reactor containment.



NEW SANS FACILITY AT HFR/HB10

Objective

The main objective of the new HFR/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.

Outline of design concept

The facility will be equipped with a cold neutron source based on Be and a Be reflector around beam tube HB10. The beam will be extended outside of the containment by means of a neutron guide, which will be shielded 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 twice the length of the present one, will significantly enhance the Q-range accessible by this facility. Finally, a new collimator will be installed for optimum resolution.

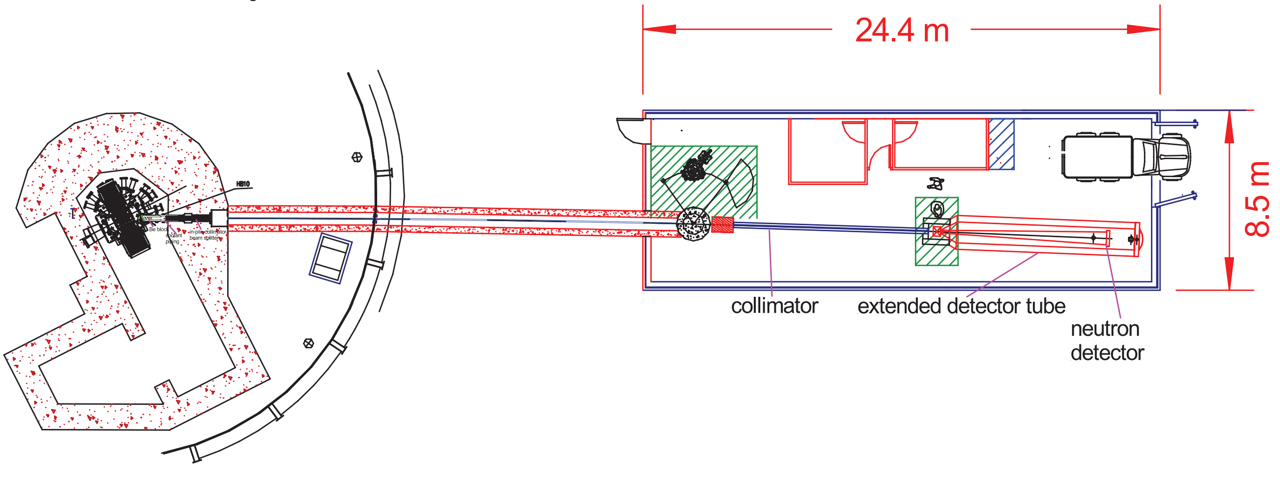
Progress in 2005

Additional studies performed in 2005, confirm that a neutron flux increase of two orders of magnitude, compared to the HB3b facility, can be expected. Based on the corresponding technical specifications, four contracts have been awarded for the development and installation of the following equipment and/or provision of the following services: a cold in-pile Be-moderator and a Be-reflector; a neutron guide of about 22 m length; a velocity selector for tuning of the neutron wavelength; preparation of high quality engineering drawings and technical specifications for the construction of a dedicated building to house the new facility.

Expected outcome

As shown in Figure 42, provision has also been made for the future installation of a neutron diffractometer within the new SANS facility building. This building is being designed to allow for handling and storage of shielding equipment, such that investigations of irradiated specimens will be possible by both SANS and neutron diffraction. This will render a unique combination of advanced experimental facilities, aiming at the assessment of irradiation impact on welded nuclear safety related specimens representative of RPV internals components, both in terms of residual stress and defects evolution. This is a key issue in managing and extending the safe plant life of ageing reactors.

Figure 42 - Layout of proposed installation of SANS facility inside a dedicated building in front of HB10



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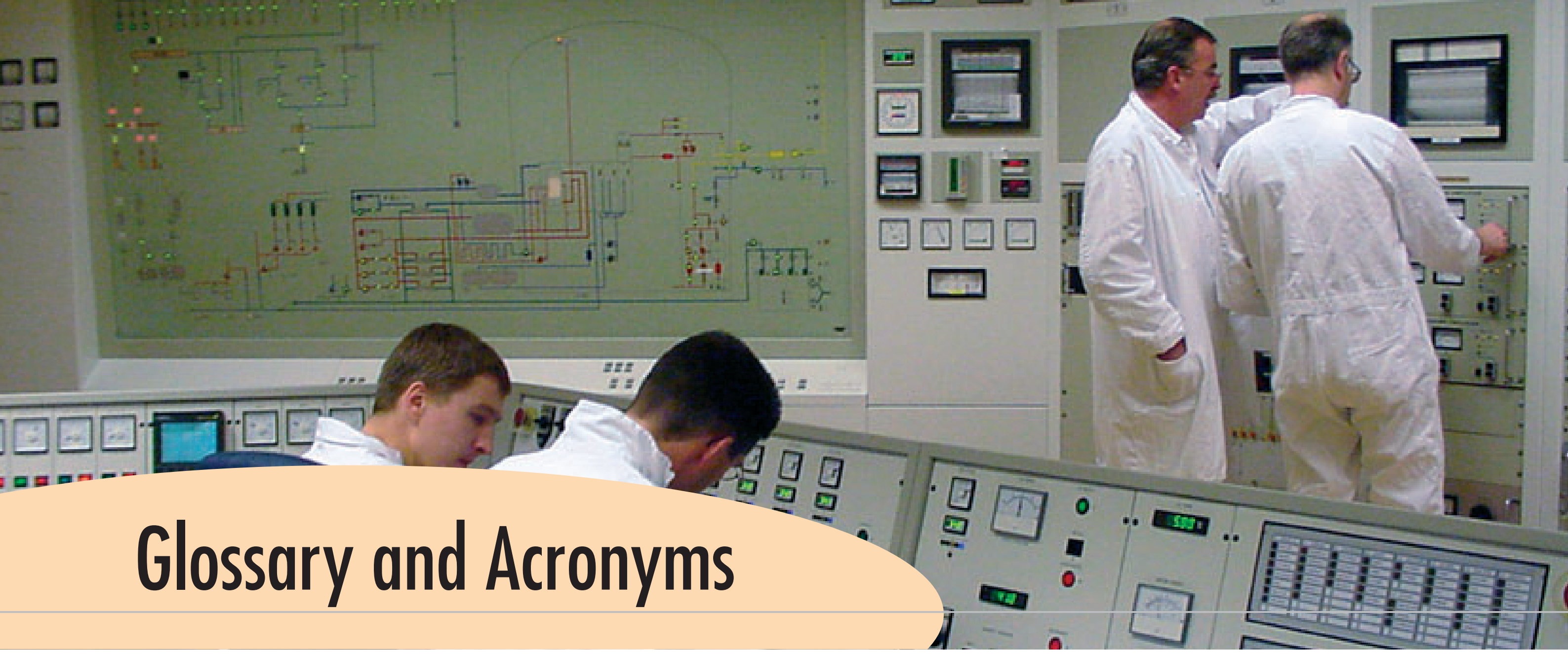
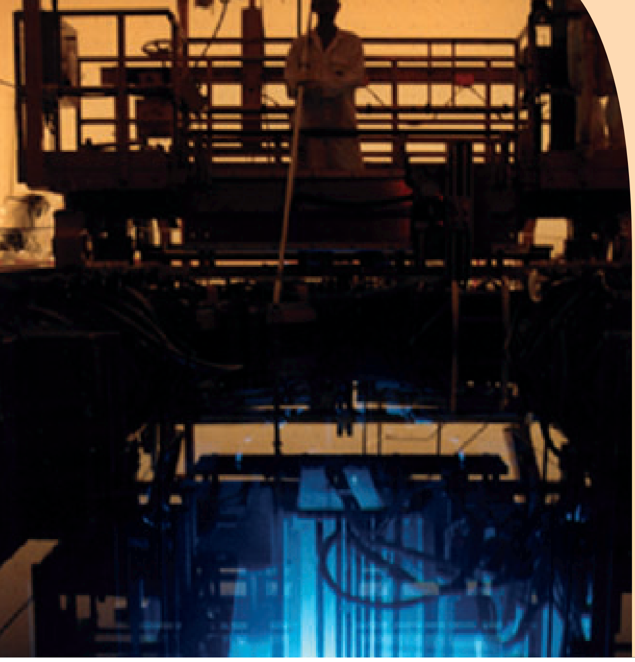
A list of HFR scientific publications mentioned in this Annual Report can be obtained upon request to the contact person.



Glossary and Acronyms

APE	Accident Pressure Equalisation
ADS	Accelerator Driven Systems
AHG	Ad-Hoc-Group
AMES	Ageing Materials Evaluation Studies
BNCT	Boron Neutron Capture Therapy
BoT	Board of Trustees
BPA	Boron compound for BNCT
BSH	Boron compound for BNCT
BWR	Boiling Water Reactor
CASHIR	Cadmium-Shielded Steel Irradiation Experiment
CEA	Commissariat à l'Energie Atomique
CEN	The European Committee for Standardization
CHIP	Chilean Irradiation Project
CMC	Ceramic Matrix Composite
COVRA	Centrale Organisatie Voor Radioactief Afval
DEMO	Demonstration Fusion Reactor
DG	Directorate General
DMW	Dissimilar Metal Welds
dpa	displacements per atom
EANM	European Association of Nuclear Medicine
EC	European Commission
ECN	Energieonderzoek Centrum Nederland
EdF	Electricité de France
EFDA	European Fusion Development Agreement
EFTTRA	Experimental Feasibility of Targets for TRAnsmutation
EMIR	European network for Medical radio-Isotopes and beam Research
ENEA	Ente Nazionale per lo sviluppo dell'energia nucleare e le Energie Alternative
ENPOWER	Nuclear Plant Operation by Optimising Weld Repairs
ENSAM	Ecole Nationale Supérieure d›Arts et Metiers
EORTC	European Organisation for Research and Treatment of Cancer
ESTRO	European Society for Therapeutic Radiology and Oncology
EU	European Union
EUROTRANS	European Transmutation
EXOTIC	EXtraction Of Tritium In Ceramics
EXTREMAT	New Materials for Extreme Environments
FIMA	Fissionable (Heavy) Metal Atoms
FLUX	Fluence Rate
FP or FWP	Framework programme
FRAME	Fracture Mechanics Based Embrittlement Trend Curves for the Characterisation of Nuclear Pressure Vessel Materials
FUJI	Fuel Irradiations for JNC and PSI
FZK	ForschungsZentrum Karlsruhe
GIF	Generation IV International Forum
HABOG	Hoogradioactief Afval Behandelings- en Opslag Gebouw
HAZ	Heat Affected Zones
HB	Horizontal Beam Tube
HDBEKWS	Hoge Druk BassinExperimenten KoelWater Systeem (high pressure pool experiments cooling water system)
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
HITHEX	High Temperature Heat Exchanger
HT	High Temperature
HTR	High Temperature Reactor
IEA	International Energy Agency
IAEA	International Atomic Energy Agency
IASCC	Irradiation Assisted Stress Corrosion Cracking
ICI	International Conference on Isotopes
IE	JRC Institute for Energy, Petten (NL)
IFMIF	International Fusion Materials Irradiation Facility
IIS	International Isotopes Society
IMRT	Intensity Modulated Radiotherapy
INET	Institute of Nuclear Energy Technology (of the Tsinghua University)
INNOGRAPH	Innovative Graphites
INSARR	Integrated Safety Assessment of Research Reactors
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
ISO	International Organization for Standardization



ITER	International Thermonuclear Experimental Reactor
ITU	Institute for TransUranium Elements, Karlsruhe
JET	Joint European Torus
JRC	Joint Research Centre
KFD	Kern Fysische Dienst
KLST	specimen for impact testing according to the German standard DIN 50115
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
MICROMOX	Mixed Oxide (MOX) Fuel with Improved Microstructure
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide
MTR	Materials Testing Reactor
MYKONOS	Molybdenum Production for Mallinckrodt Diagnostica
NAP	Normaal Amsterdams Pijl (sea level)
NCT	Neutron Capture Therapy
NCTPlan	Neutron Capture Therapy Treatment Planning
NESC	Network for Evaluating Structural Components
NET	Network on Neutron Techniques Standardisation for Structural Integrity
NRG	Nuclear Research and consultancy Group
PIE	Post Irradiation Examinations
PISA	Phosphorus Influence on Steel Ageing
PMMA	Polymethyl methacrylate
PROFEET	Prototype LEU Fuel Test
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
SAFELIFE	Safety of Aging Components in Nuclear Power Plants
SAFETY-INNO	Safety of Innovative Reactor Designs
SANS	Small Angle Neutron Scattering
SCWG	Safety Culture Working Group
SCWR	Super Critical Water cooled Reactor
SICCROWD	SIC-SiC composites, Chromium and tungsten (W) irradiation
SPICE	Sample Holder for Irradiation of Miniaturized Steel Specimens
SPIRE	Spallation and Irradiation Effects
STROBO	Stress Relaxation of Bolt Materials
SUMO	In-Sodium Steel Mixed Specimens Irradiation
TBM	Test Blanket Modules
TC	Technical Committee
TG	Task Group
TIRO	Thermal Flux Irradiation Device for Radioisotopes Production
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
VU Amsterdam	Vrije Universiteit Amsterdam
VROM	Netherlands Ministry of Housing, Spatial Planning and the Environment
VVER	Russian Pressurized Water Reactor
WWER	Water Water Energy Reactor

European Commission

EUR 22297 EN - DG JRC - Institute for Energy
Operation and Utilisation of the High Flux Reactor
Annual Report 2005
Edited by: R. Moss, G. Gouwens - van Rijn, R. May
Luxembourg: Office for Official Publications of the European Communities
2006 - 40 pp. - 21 x 29.7 cm
Scientific and Technical Research Series
ISBN 92-79-02659-3
ISSN 1830-5997

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 2005 a new operation licence has been granted under the Dutch Nuclear Energy Law.
In the beginning of the year, following a request of JRC, IAEA conducted a full-scope INSARR mission, which assessed and acknowledged the safety of the HFR.
2005 was also the year of the successful start of the progressive core conversion from high to low enriched uranium.
Other 2005 highlights include:
- *299 operational days*
- *239 visits, including representatives from the neighbouring municipalities*
- *Several European Networks managed*
- *Various fusion and fission related irradiation experiments carried out*

15

LD-NA-22297-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.

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ISBN 92-79-02659-3

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