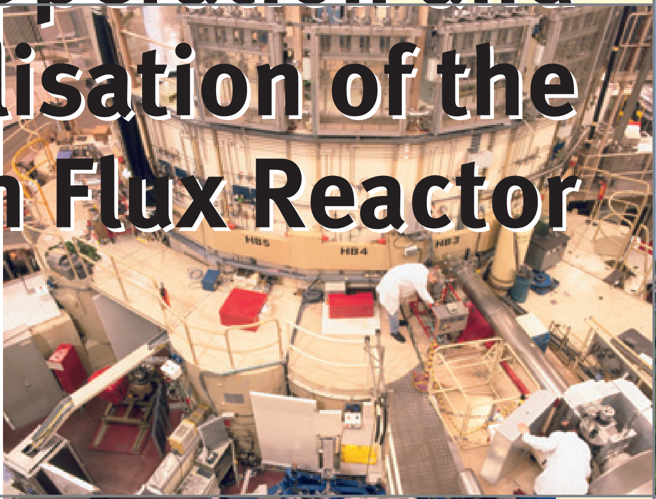
ISSN 1018-5593
ISSN 1830-5997

Operation and Utilisation of the High Flux Reactor



Annual Report 2009

JRC
EUROPEAN COMMISSION

Institute for Energy

EUR 24513 EN

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Legal notice

Luxembourg: Publications Office of the European Union, 2010

European Commission

EUR 24513 EN
ISSN 1018-5593
ISSN 1830-5997
DOI 10.2790/23845
ISBN 978-92-79-16579-5

Printed in the Netherlands, Aranea Grafimedia

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HFR: Reactor Management

HFR Operation and related services

At the start of 2009, all the investigations and inspections of the bottom plug liner showed clearly that a safe start and subsequent operation, under strict conditions, of the HFR were possible. Due to increasing shortage of radioisotopes and on urgent request of the radioisotopes producers, authorization was given by the Dutch competent authorities to operate the HFR.

The planned operational cycle pattern consisted of a scheduled number of 249 operation days and two maintenance periods of respectively 42.6 and 31.3 days. In 2009 therefore, the HFR was in operation for 248 days (Figure 1).

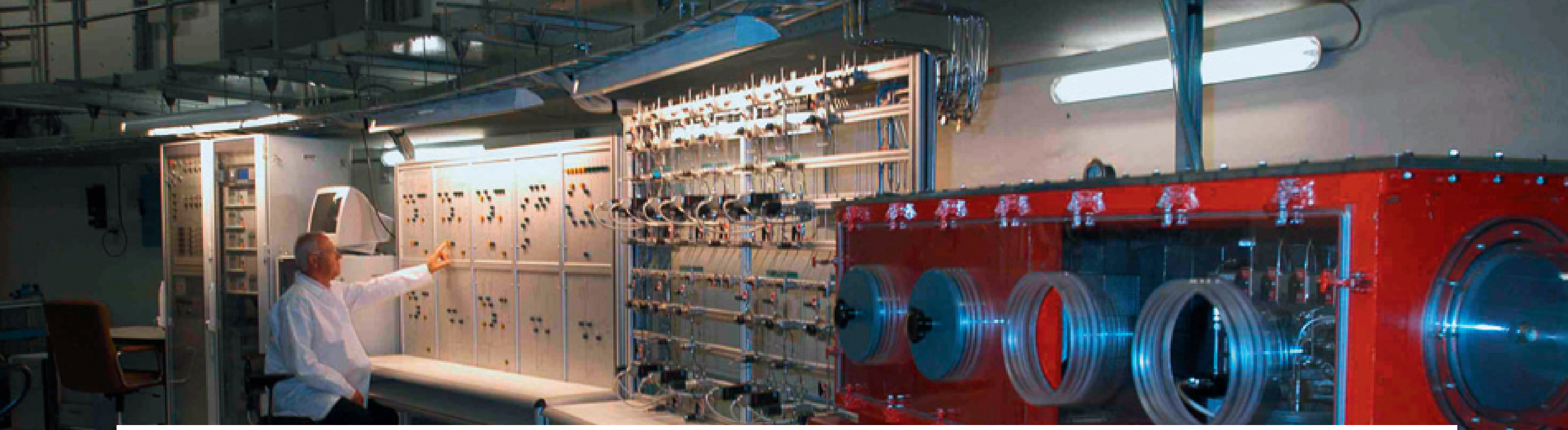
The reduction of operating time can be almost completely attributed to the investigation and inspections of the bottom plug liner which caused the extended shutdown and the later start of HFR cycle 09.02. After deliberation between physicians and on request of the major radioisotope producers, the maintenance period between HFR cycle 2009-01 and HFR cycle 2009-02 was extended to 31 March 2009. The objective of this change of cycle pattern was to ensure the availability of sufficient irradiation capacity at the end of cycle 2009-02. This corresponds to an actual availability of 67.97 % with reference to the scheduled operation plan. Nominal power has been 45 MW, with a total energy production of approximately 11 135.21 MWd, corresponding to a fuel consumption of about 13.9 kg ^{235}U.

At the beginning of the reporting period, HFR operations were temporarily stopped due to the final part of the investigation and inspection of the bottom plug liner and the performance of the annual containment leak test. Nevertheless, all the 2009 cycles were started according to the original schedule. During the summer maintenance period, the extended reactor vessel inspection of the bottom

Table 1 - 2009 operational characteristics

			OPERATING TIME					SHUT-DOWN TIME				
Cycle Begin-End	HFR Cycle	Generated Energy	Planned	Low Power	Nominal Power	Other Use	Total	Planned	Unsche-duled	Number of Interruptions		Stack Release (of Ar-41)
2009		MWd	hrs	h.min	h.min	h.min	h.min	h.min	h.min	PD	Scram	Bq x E+11
01.01 - 11.02	Investigation and inspection and maintenance period					1008.00		16.00	00.18		2	4.1
12.02 - 12.03	09.01	1292.32	696	04.05	662.40		666.45	29.15				4.2
13.03 - 26.04	09.02	1124.45	640	02.34	599.31		602.05	476.55				4.1
27.04 - 30.05	09.03	1384.78	736	01.40	737.50		739.30	76.30				4.9
31.05 - 27.06	09.04	1111.80	592	02.13	592.00		594.13	77.47				5.3
28.06 - 18.07	09.05	792.56	424	02.28	421.35		424.03	79.57				4.2
19.07 - 17.08	Maintenance period and ISI					696.00		150.38	00.04		1	5.3
18.08 - 08.09	09.06	992.63	568	01.58	529.01		530.59	16.18	04.43		2	3.7
09.09 - 16.10	09.07	1505.69	760	01.45	802.00		803.45	108.15				6.0
17.10 - 13.11	09.08	1114.37	592	03.10	592.06		595.16	77.35	00.09	1	2	4.2
14.11 - 18.12	09.09	1411.49	760	02.16	752.41	01.22	756.19	83.36	00.05		1	5.4
19.12 - 31.12	09.10	402.12	248	01.51	239.39		241.30	70.30				
TOTAL :		11135.21	6016	24.00	5929.03	01.22	5954.25	17.92.38	1012.57		5	42.0
Percentage of total time in 2009 (8760 h) :				0.27	67.68	0.02	67.97	20.46	11.56			
Percentage of planned oper. time (6016 h) :				0.40	98.55	0.02	98.98					

**PD: Power decrease*



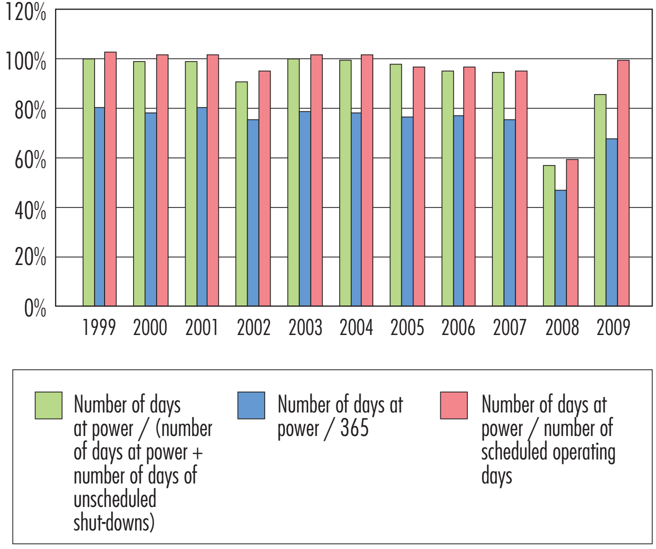


Figure 1 - HFR availability

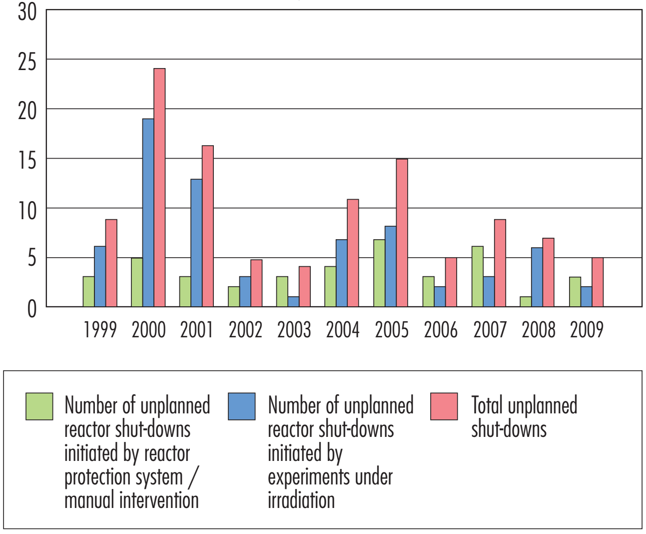


Figure 2 - HFR unscheduled shut-downs

plug liner and several safety related modifications were successfully performed.

After the scheduled end of each cycle, the shut-downs included activities performed in the framework of the regular HFR operators' training.

The detailed operating characteristics for 2009 are given in Table 1. All details on power interruptions and power disturbances, are given in Table 2. It shows that 5 scrams and one manual power decrease occurred (see also Figure 2). Two of these scrams were due to manual intervention and a human error respectively. Two others were caused by loss of off-site power. The remaining scram was due to intervention of the reactor instrumentation devices to ensure safety.

Besides the regular visits of international colleagues and relations with the medical world, a total of 914 visitors (divided over 162 tours) were guided through the reactor during 2009.

Maintenance activities

In 2009, the maintenance activities consisted of the preventive, corrective and breakdown maintenance of all Systems, Structures and Components (SSCs) of the HFR as described in the annual and long term maintenance plans. These activities are executed with the objective to enable the safe and reliable operation of the HFR and to prevent inadvertent scrams caused by insufficient maintenance.
The periodic leak testing, as one of the licence requirements (0.2 bar overpressure for 24 hours duration) and the extended In-Service Inspection, including measurements on the bottom plug liner, were performed successfully. As part of the HFR Modification Plan, several modifications were completed.

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

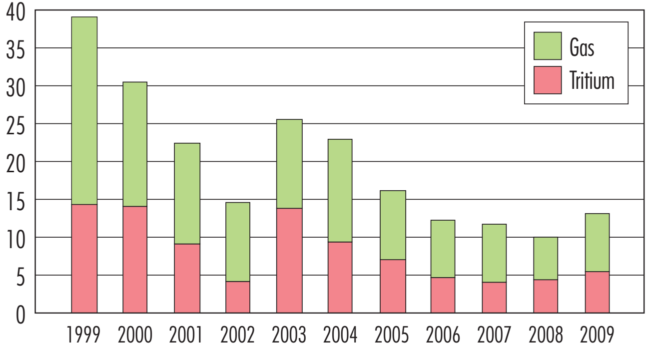
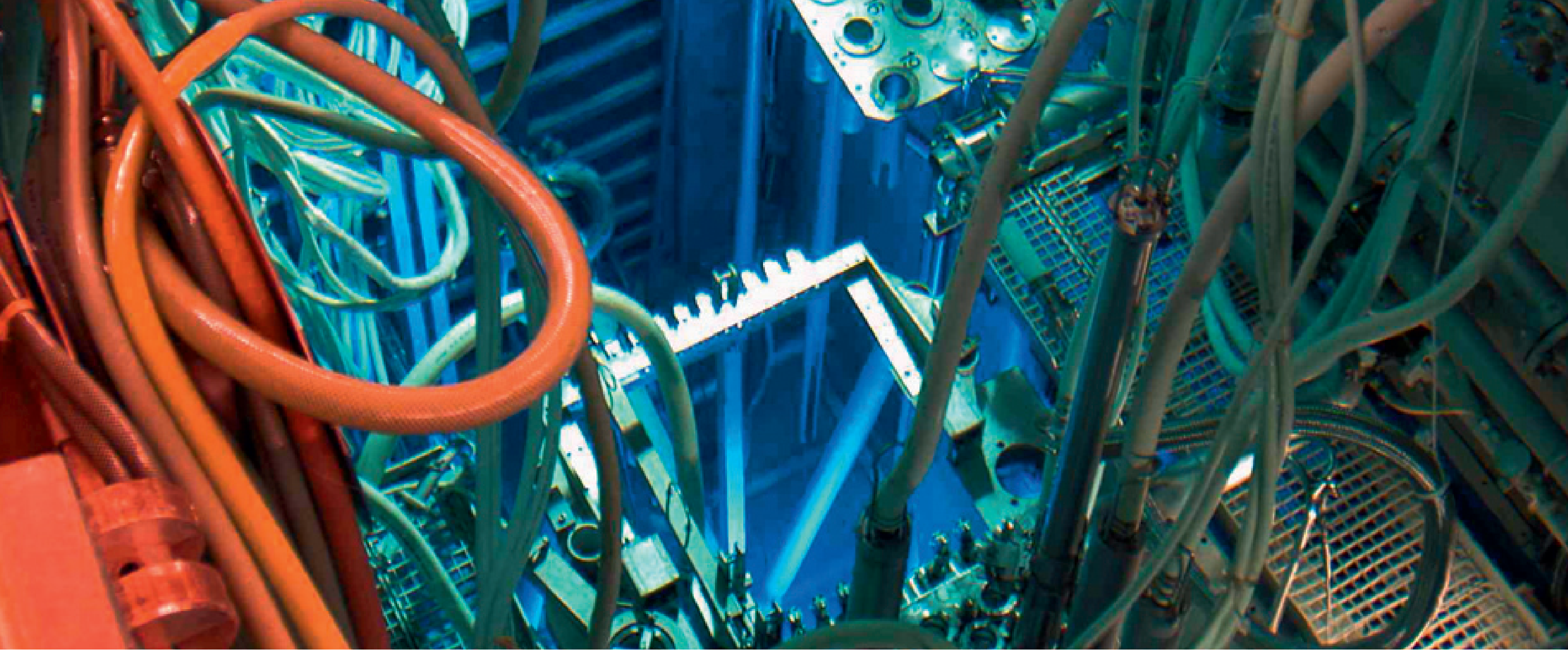


Figure 3 - Radioactivity discharged (licence limit 100 Re/year)



DATE	CYCLE	TIME OF ACTION	RESTART OR POWER INCREASE	NOMINAL/ ORIGINAL POWER	ELAPSED TIME TO		DISTURBANCE CODE				REACTOR SYSTEM OR EXPERIMENT CODE	COMMENTS
					RESTART OR POWER INCREASE	NOMINAL/ ORIGINAL POWER	1	MW	2	3		
2009		hour	hour	hour	h.min	h.min						
21 Aug	09.06	13.50	13.54	14.05	00.04	00.15	AS	0	E	H	Exp. 266-09	Due to manipulations with PSF experiment 266-09 the coolant system of this experiment was disturbed, which resulted in a scram.
08 Sept	09.06	19.21					AS	0	A	E	Mains power supply	Loss of off-site main power supply (10kV) causing a reactor scram.
22 Oct	09.08	13.49		13.53		00.04	MP	36	R	H	Power demand	During manipulations of experiment TYCOMO the power demand was switched off and was not put into automatic control, due to reactivity effects the reactor power decreased to 36 MW. After switching back into remote control the reactor power was operated to nominal power.
28 Oct	09.08	19.45	19.48	20.00	00.03	00.15	AS	0	E	H	Exp 266-08	During execution of the check-out of experiment INCOMODO (354-01) the temperature mV-unit of PROMETEO 8 (266-08) was adjusted by mistake, with a scram as result.
05 Nov	09.08	02.43	02.49	03.08	00.06	00.25	AS	0	R	I	Primary flow <90%	Scram on primary flow <90% without any signal on ann. AM-02. Reactor restarted after the primary pressure and flow was checked.
25 Nov	09.09	22.51	22.56	23.12	00.05	00.21	AS	0	A	E	Mains power supply	Loss of off-site main power supply (10kV) causing a reactor scram.

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

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

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

Table 2 - 2009 full power interruptions of HFR

Figure 4 - MTR2 container at COVRA on its way to the docking station underneath the hot cell of HABOG

Fuel Cycle

Front end

During 2009, due to the shutdown of the HFR, only 5 Low Enriched Uranium (LEU) fuel elements and 4 control rods were inspected at the manufacturer's site and delivered to Petten. Since May 2006, the HFR is running completely on LEU fuel.

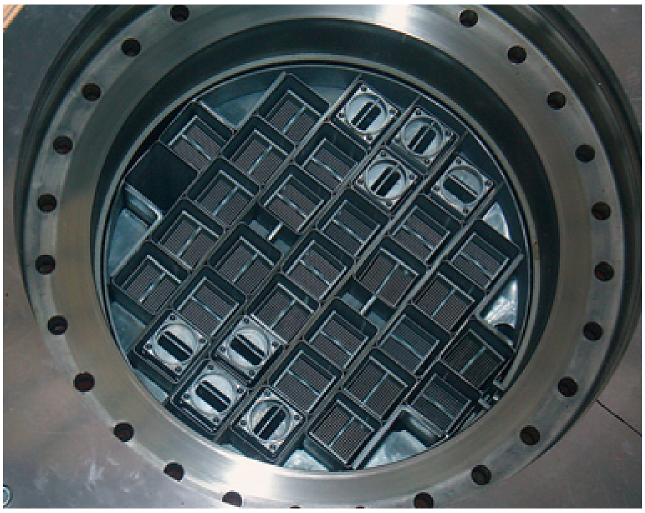


Figure 5 - Basket filled with fuel elements and control rods inside the MTR2 cask

Back end

In 2009, two shipments with High Enriched Uranium (HEU) spent fuel took place in MTR2 containers to the Dutch Central Organisation for Radioactive Waste (COVRA); in total 66 elements, of which 59 fuel and 7 control rods, equivalent to two positions in the HABOG building for High Level Radioactive waste at COVRA. At the end of 2009, 26 positions out of the 48 positions (including the 6 reserve positions) are vacant in the HABOG. The last 18 HEU elements, still present in the HFR pool, are planned to be shipped in 2010.

The Gesellschaft für Nuklear-Service (GNS) carried out the compulsory 3 years inspection of the shock absorbers which are mounted around a loaded cask during a transport. The shock absorbers needed a second inspection which required the building of a special device that prevents deformation during the pressure test.

Figure 6 - The sea container, holding the MTR2 container during transports, is unloaded

Figure 7 - The basket holding HEU elements is ready to be loaded into a canister in the hot cell at COVRA

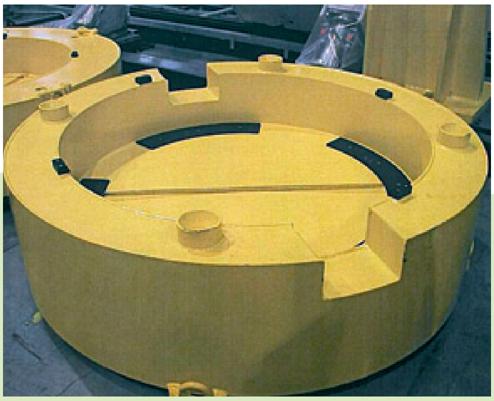


Figure 8 - One of the shock absorbers during an inspection at GNS in Mülheim

Figure 9 - 16th NeT Steering Committee Meeting, Hotel Marijke, Bergen, NL, Nov. 2009

HFR Supporting Networking in Research

Network on Neutron Techniques Standardization for Structural Integrity (NeT)

NeT, the European Network on Neutron Techniques Standardization for Structural Integrity, supports progress towards improved performance and safety of European energy production systems. To this end, the JRC, next to its role as manager of NeT, contributes to the scientific work through neutron scattering for residual stress measurement and assessment of thermal material ageing effects, using its beam tube facilities at the HFR. In addition, in 2009, the JRC started its contributions to synchrotron X-ray diffraction measurements performed at synchrotron facilities in France and Germany.

About 35 organisations are actively participating in the work of NeT, including eight organisations from the new member states, three organisations from candidate countries, one from Russia, one from Japan, one from Australia, and one from South Korea. In 2009, the NeT Steering Committee (Figure 9) met twice and significant progress has been made in carrying out the work within its Task Groups (TGs). In November 2009, an Enlargement and Integration Workshop has been organised attended by about 15 scientists from the EU and Turkey.

In 2009, the main experimental activities in NeT were within the newly established TGs 4 and 5. TG4 focused on a 3-bead in a slot weld in a stainless steel plate while TG5 dealt with an autogenous weld along the edge of the ferritic steel beam. Several contributors, including JRC, provided experimental assessment of welding residual stresses and welding distortion for these specimens.

Based on the work performed in TG1 on a single bead weld on a plate, a dedicated issue of the International Journal of Pressure Vessels and Piping has been published in 2009 [1]. It includes, among others, 14 papers from the participants of NeT. NeT TG1 is now also becoming an example case in the weld modelling section of the R6 defects assessment procedure in the UK, and it has also been suggested to be considered as a sample case for a NAFEMS numerical analysis standard for welding residual stresses.

In the course of 2009, first contacts have been established with the US Nuclear Regulatory Commission (NRC), to the IAEA and to the International Institute of Welding (IIW) with a view to assessing the possibilities for a future involvement of these organizations in NeT.

The HFR irradiation possibilities were used to perform residual stress measurements by neutron diffraction, as explained in the next chapter.

FAIRFUELS, towards a more sustainable fuel cycle with less nuclear waste

In the frame of the EURATOM 7th Framework Programme (FP7), the 4-year project FAIRFUELS (Fabrication, Irradiation and Reprocessing of FUELS and targets for transmutation) aims at a more efficient use of fissile material in nuclear reactors by implementing transmutation. Transmutation provides a way to reduce the volume and hazard of high level radioactive waste by recycling the most long-lived components. In this way, the nuclear fuel cycle can be closed in a sustainable manner. The FAIRFUELS consortium consists of ten European research institutes, universities and industry. The project started in 2009 and is coordinated by NRG. Both NRG and JRC-IE work closely together on the HFR irradiations that are scheduled in FAIRFUELS: MARIOS and SPHERE fuel irradiations, as described in the following chapters.

HFR as a Tool for Research

RESIDUAL STRESS MEASUREMENTS BY NEUTRON DIFFRACTION AT THE HFR

In 2009, the HFR facilities for residual stress measurement by neutron diffraction at beam tubes HB4 and HB5 have been used for a number of measurement campaigns. Three examples are outlined briefly, as follows:

In the context of NeT Task Group 5 (see previous chapter), residual stress/strain measurements have been performed across the width of a 10 by 50 mm^2 cross section ferritic steel beam with an autogenous weld along one of its edges. These measurements are part of a TG5 residual stress measurement round-robin, where the experimental results shall aid the validation of numerical stress prediction procedures. Indeed, prediction procedures are complicated in the case of such ferritic steels because of the involvement of phase transformations during various stages of the welding process. Figure 10 compares measurements and modelling of the strains in welding longitudinal direction. The results were published at the ASME Pressure Vessels and Piping Conference in 2008 [04].

A second series of measurements, performed in 2009, targeted developments of improved measurement procedures for multi-pass welds in stainless steel, as they are often used in assembling primary cooling systems in nuclear power installations. The inhomogeneity of the weld material and the sheer size of such components complicate significantly the experimental determination of the welding residual stresses. The specimens used in these measurements were slices cut from a bi-metallic – ferritic to austenitic steel – piping weld whereby, in this case, a stainless steel clad layer was applied on the inner surface of the ferritic part of the pipe. Figure 11 shows a cross section of the actual specimen, including the weld, and indicates the measured distribution of strains in the welding transverse direction in the ferritic part.

Finally, an IAEA driven collaborative research project (CRP), with participation of the JRC, on research reactors and the capabilities for residual stress measurement has been concluded in 2009. The JRC assumed responsibility for the organization of ongoing round robin exercises to benchmark the performance of the participating facilities. Nine or ten reactor based neutron sources are expected to participate in the round robin exercises within the coming one or two years. The contribution of the HFR to this first round robin exercise (an interference fit of an aluminium ring and plug) has been performed in spring 2009. This round robin reiterates a corresponding exercise in the context of VAMAS TWA20 in the late 1990's (see also HFR annual report 1998), and the data from 2009 are in good agreement with those measured at that time.

In 2009, NRG has also continued to perform structural analyses by powder diffraction using the diffractometer of beam tube HB3a. Among others, materials for electricity

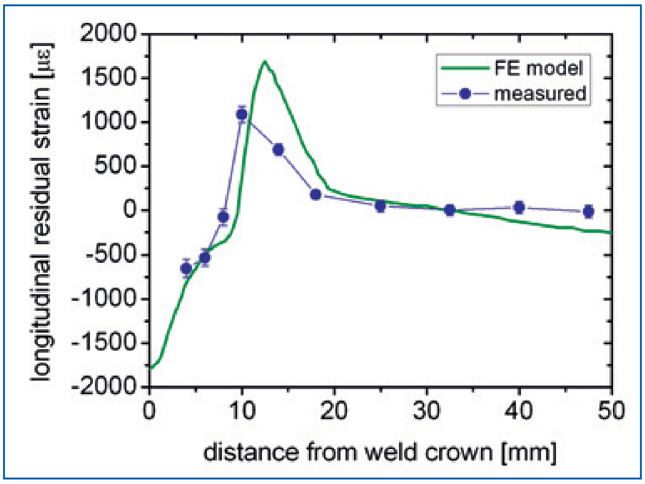


Figure 10 - Longitudinal strains in an autogenously welded ferritic steel beam, HFR neutron diffraction measurements compared to FEM results

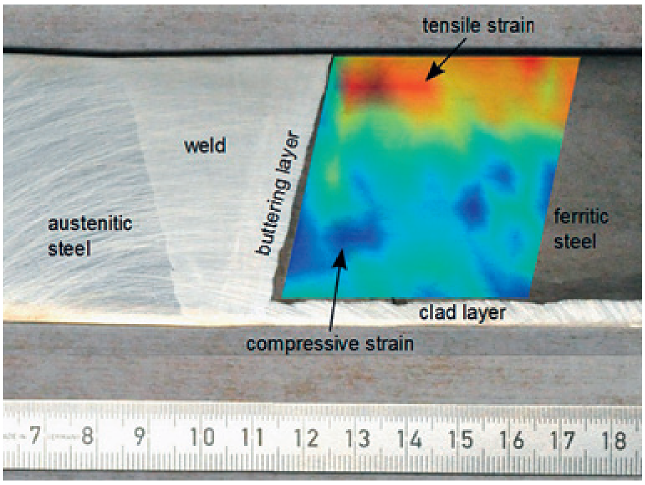


Figure 11 - Distribution of strains in the welding transverse direction in a slice of a mock-up of a primary cooling system weld connection between a ferritic and an austenitic steel pipe

Figure 12 - Assembly of the CRYO experiment

storage applications have been investigated upon request of Leiden University. On the same instrument, a powder diffraction spectrum of lithium hydride, a candidate material for hydrogen storage, was measured on behalf of the JRC Cleaner Energies Unit

CRYO EXPERIMENT: ALPHA-EMITTERS RADIOTOXICITY REDUCTION

Objective

Research conducted to date tends to suggest that the decay half-life of alpha-emitting isotopes embedded in a metallic matrix may be reduced at cryogenic temperatures. If confirmed, this may ultimately contribute to the reduction of nuclear waste.

To avoid any possible speculations, JRC is trying to verify the status/outcome of these studies by conducting an experiment in the HFR, called CRYO. The CRYO irradiation will produce ^{210}Po, which is a pure alpha emitter, embedded in a metallic matrix of copper. This will be achieved by the irradiation of eight copper – bismuth disks and transmutation of ^{209}Bi.

Achievements 2009

Irradiation of the CRYO experiment started on 22 December 2009, for a duration of one HFR cycle (~29 full power days).

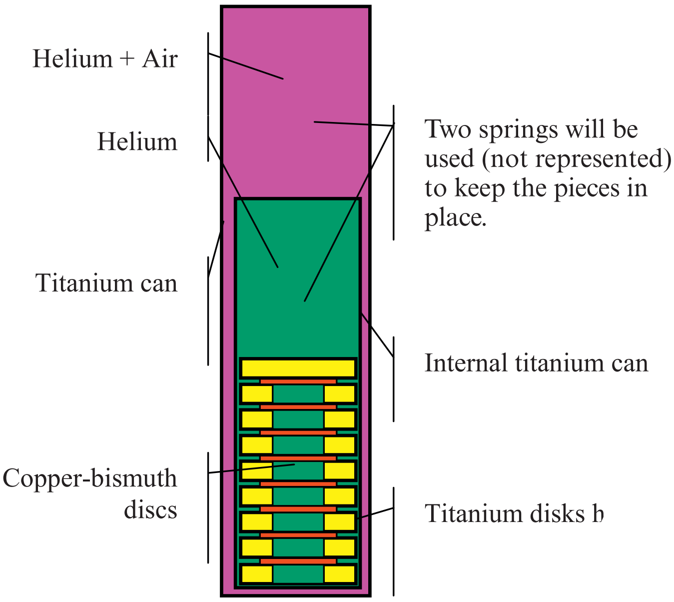


Figure 13 - CRYO experiment layout

Figure 14 - Assembly of the CRYO experiment

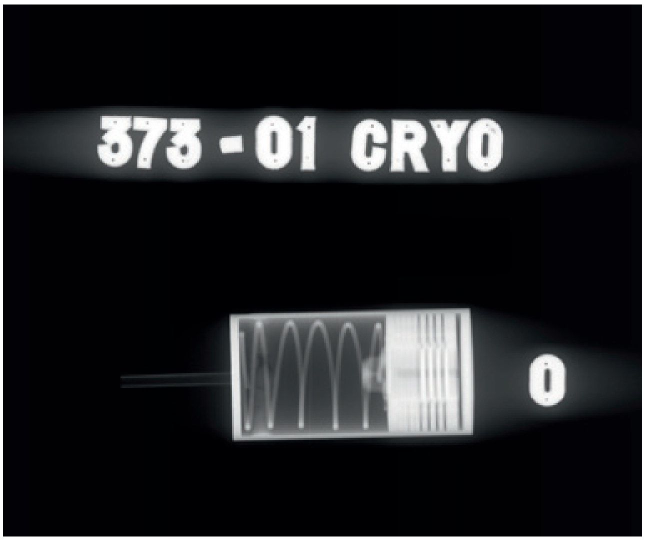


Figure 15 - Radiography of the CRYO experiment

Fuel Irradiations in the HFR

HELIOS FUEL EXPERIMENT: AMERICIUM TRANSMUTATION

Objective

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

1. Provide release pathways by creating open porosities, i.e. release paths to the plenum gas. Therefore, in the HELIOS test matrix a composite target with a MgO matrix containing a network of open porosity has been included.
2. Increase target temperature to promote the release of helium from the matrix. Americium or americium/plutonium zirconia based solid solutions along with CerMet targets have been included in the test matrix to study the effects of the temperature. Adding plutonium allows for fission, which will increase the target temperature at the beginning of irradiation (BOI).

Achievements 2009

Irradiation of the HELIOS experiment started on 29 April 2009 and will last about 250 full power days, i.e. until the HFR stop, foreseen for 19 February 2010.

The start-up of the experiment has been flawless. During the first cycle, the experiment has showed a higher neutron flux than expected. Investigations are being conducted and will be finalised with the measurement of the fluence detectors installed near to each test pin. This higher flux does not jeopardise the results of the experiment. As a matter of fact, it might even help as the experiment will receive more neutron fluence than expected. This will counteract the premature stop by raising the burn-up and helium production.

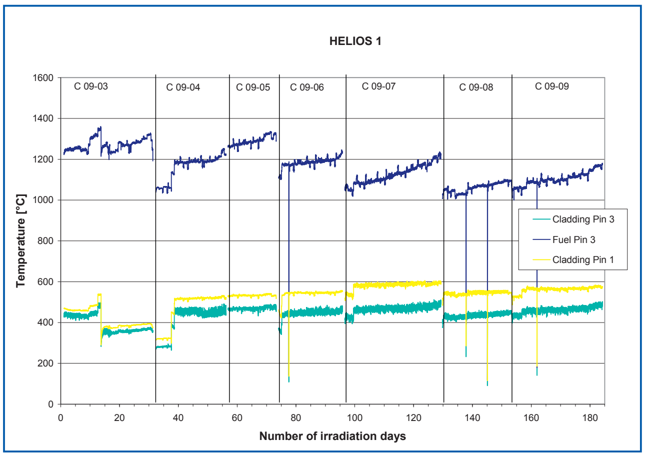


Figure 16 - Temperature readings of pins 1 and 3 of the HELIOS1 experiment

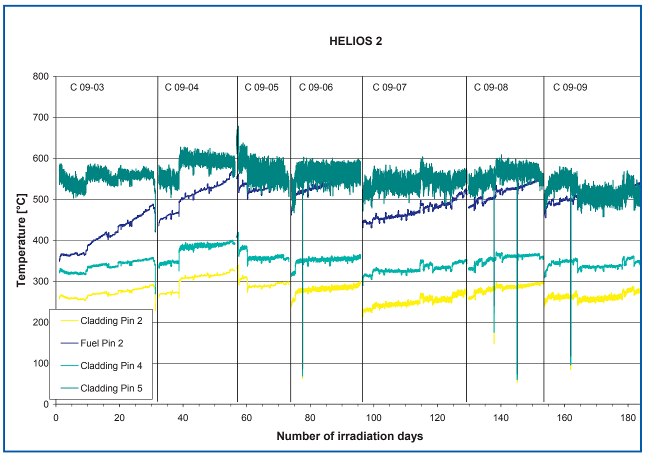


Figure 17 - Temperature readings of pins 2, 4, and 5 of the HELIOS2 experiment

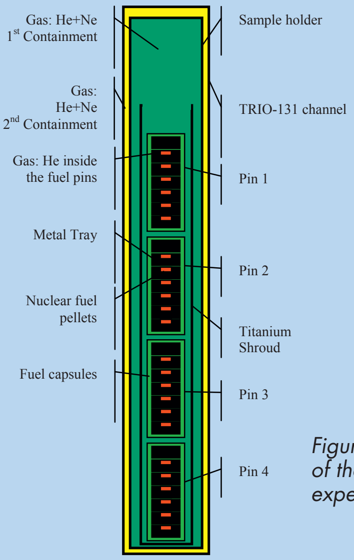


Figure 18 - Schematic view of the MARIOS irradiation experiment

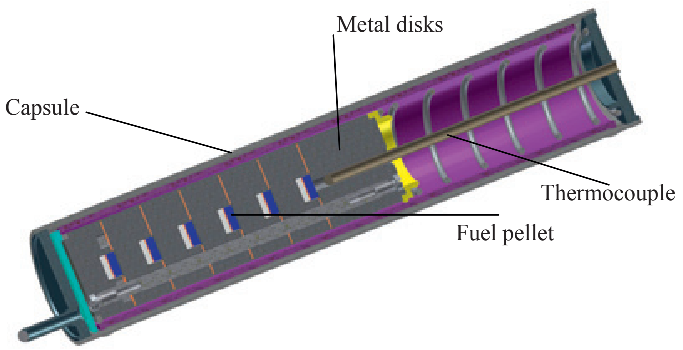


Figure 19 - Computer-aided impression of a MARIOS capsule

MARIOS FUEL IRRADIATION: MINOR ACTINIDE RECYCLING

Objective

The MARIOS irradiation programme, as part of FAIRFUELS, is a series of irradiations dealing with heterogeneous recycling of Minor Actinides (MAs) in Sodium-cooled Fast Reactors (i.e. the MA-bearing-blanket concept). MAs, such as americium and curium, are not always recycled and remain key elements composing the waste. The aim of the MARIOS irradiation is to investigate the behaviour of MA targets in a uranium oxide matrix carrier. For the first time, americium (^{241}Am) is included in a (natural) uranium oxide matrix $Am_{0.15}U_{0.85}O_{1.94}$. This irradiation will produce large amounts of helium within the targets. Its goal is therefore to study the fuel behaviour in terms of helium production and swelling. These may cause significant damage to the material under irradiation. The MARIOS irradiation will start in autumn 2010 and will last for approximately 300 full power days.

Achievements 2009

During 2009, the preliminary design of MARIOS was finalised. Figure 18 shows a schematic drawing of the layout of the experiment. Figure 19 shows an impression of a single capsule. The nuclear analyses have been concluded and the fission power generated by the fuel pellets has been calculated (see Figure 20). The fuel pellets, made by CEA in France, are in preparation and will arrive in Petten during spring 2010.

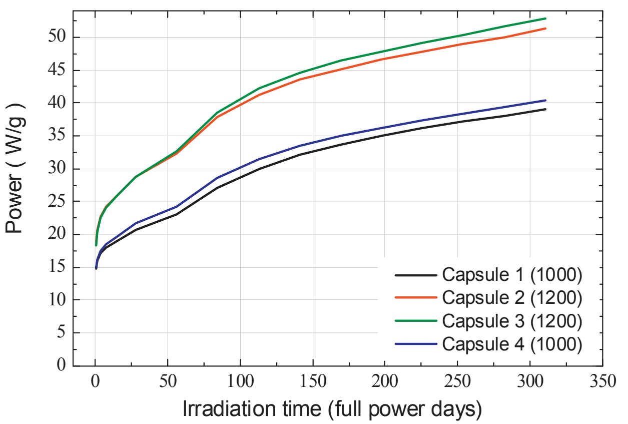


Figure 20 - Simulated power history of the MARIOS pins

SPHERE FUEL IRRADIATION: SAFER FUELS

Objective

Within the FP7 FAIRFUELS project, the irradiation SPHERE has been planned for 2011. SPHERE has been designed to compare conventional pellet-type fuels with so-called sphere-pac fuels. The latter have the advantage of an easier, dust-free fabrication process. When dealing with highly radioactive minor actinides, dust-free fabrication processes are especially essential to reduce the risk of contamination.

To assess the irradiation performance of Sphere-Pac fuels compared to conventional pellet fuel, a dedicated SPHERE irradiation experiment will be performed. For this purpose, americium-containing fuel, both pellet and sphere-pac types, will be fabricated at JRC-ITU in Germany. These fuels will be irradiated in the HFR. This irradiation is the first of its kind, as no minor actinide bearing Sphere-Pac fuel has ever been irradiated before. The SPHERE irradiation will last for approximately 300 full power days.

Achievements 2009

The preliminary design for the SPHERE irradiation experiment has started and the first fabrication trials have started.

HTR FUEL PEBBLE IRRADIATION HFR-EU1

Objective

After a pause of several years, after the end of the German fuel qualification programme, JRC-IE resumed in 2004 new HTR fuel irradiations in the HFR, this time with a focus on determining the limits of old and newly produced fuel in terms of temperature and burn-up for possible use in advanced pebble bed HTRs with very high coolant outlet temperature (up to 1000°C) and improved sustainability. A first experiment with 5 German AVR fuel pebbles (HFR-EU1bis) was completed in 2005 and followed by a second (HFR-EU1) to be completed in early 2010 which investigates higher burn-up tolerance of existing German pebbles and of newly produced Chinese fuel. In Table 3, the basic irradiation characteristics are compared and in the section below, some key comparative data is described.

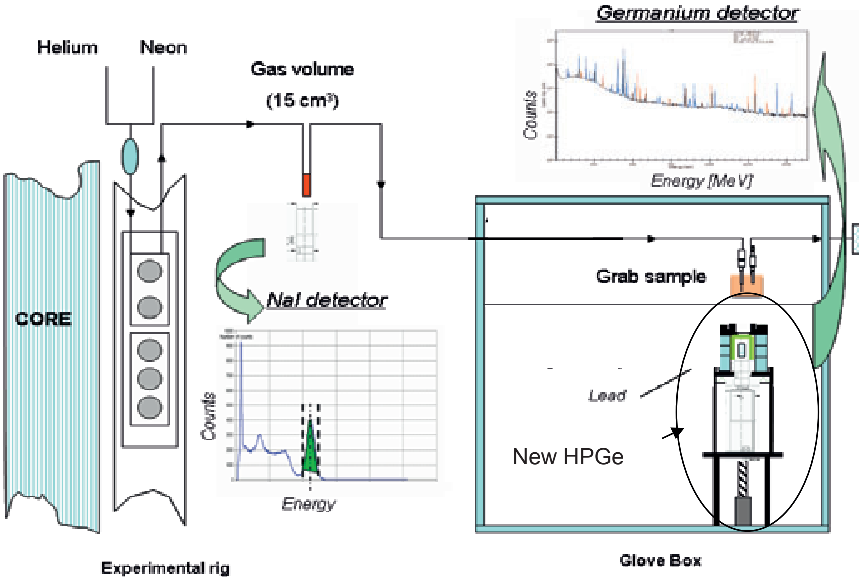


Figure 21 - Sketch of the gamma spectrometry station for fission gas release analysis

In the HFR-EU1 experiment [3], the irradiation targets are 5 pebbles irradiated in 2 separately controlled capsules. Two of the pebbles were of recent Chinese production (INET), the other three of former German production (AVR). Both fuel types were tested to higher burn-up but at lower temperature than in HFR-EU1bis. Contrary to HFR-EU1bis, in this test, the fuel *surface* temperatures were kept constant at 900°C (INET) and 950°C (AVR). These conditions are more benign for the fuel, because increasing burn-up causes decreasing central fuel temperature with time. The initially targeted burn-up was 17% FIMA (INET) and 20% FIMA (AVR) which is significantly higher than the licence limit of the HTR-Modul (approx. 8% FIMA). In the course of the experiment, this objective had however to be reduced due to excessive irradiation time requirements and technological difficulties, notably with premature thermocouple drop-outs. In early 2008, massive thermocouple failure in the capsule containing AVR pebbles had put the experiment on hold for 1.5 years.

Achievements 2009

The above failure meant that a new safety case had to be made and to implement and qualify new safety instrumentation including up-to-date HPGe gamma spectrometry (Figure 21) for fission gas release analysis (Figure 22). This new installation allowed permanent fission gas release monitoring of the capsules. So far, the measured release over birth values (R/B) remained consistently low in both capsules, thus hinting at the absence of particle failure even at the already achieved high burn-ups.

The irradiation could eventually be resumed at the end of 2009 with a foreseen end of irradiation in February 2010, just before the planned HFR outage.

After termination of the experiment, the irradiation capsule will be dismantled and transported to JRC-ITU (Karlsruhe) for further PIE and safety testing as schematically shown in Figure 26.

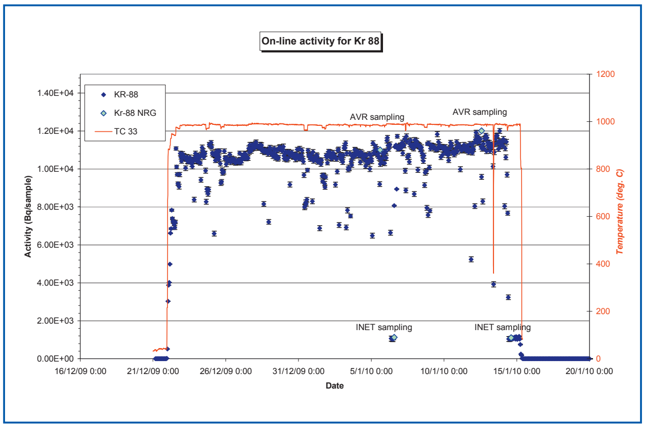


Figure 22 - Typical Kr-88 release plot hinting at undamaged particles in HFR-EU1

Table 3 - Comparison of HFR-EU1 and HFR-EU1bis fuel irradiations

	HFR-EU1bis	HFR-EU1
pebble number and type	5 AVR	2 INET + 3 AVR
start	09.09.2004	30.09.2006
end	18.10.2005	19.02.2010
duration [efpd]	250	445
burn-up [%FIMA]	9.34 – 11.07 (measured)	9.3 – 14.13 (measured)
Temperature [°C]	1250 (central)	900 (INET) 950 (AVR) (surface)
Release over birth values (R/B) at end of irradiation (based on ^{85m}Kr release	approx. 4×10^{-6}	approx. 5.5×10^{-8} (INET) approx. 1.6×10^{-7} (AVR)

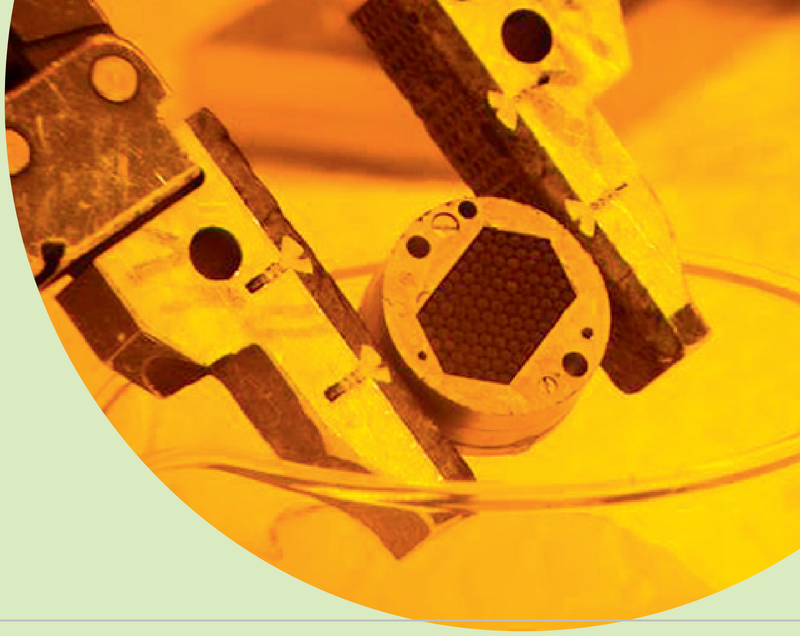


Figure 23 - PYCASSO-I dismantling, showing irradiated CEA samples in sample holder disk, in the NRG Hot Cell Laboratory

Fuel and Reactor Structural Materials

PYCASSO EXPERIMENTS: FOR TIGHTER HTR FUELS

Objective

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

Achievements 2009

PYCASSO-I has been removed after a very successful irradiation in April 2009. The complex dismantling started in autumn of the same year. An impression from the hot cells is shown in Figure 23.

During the autumn of 2009, the PYCASSO-II experiment has been introduced into the HFR reactor core. Based on the already excellent performance of PYCASSO-I, some improvements have been introduced, which has resulted in an even more uniform temperature distribution in the different sections in the experiment. As in PYCASSO-I, the PYCASSO-II irradiation targets temperature regions of 900, 1000 and 1100°C, and contains 76 separate particle sample holders. For the CEA particles a larger fluence difference has been envisaged, which has been achieved by moving one CEA section lower in the experiment, and thus at a lower flux level in the HFR core. This section is intended to receive a fluence similar to the maximum fluence in PYCASSO-I, for reference, whilst the other sections will receive a higher fluence by increasing the irradiation duration.

An overview of the PYCASSO-II irradiation is shown in Figure 24. The irradiation has been somewhat delayed by the HFR repair, and will continue with 2 or 3 more cycles after the repair, hence ending at the end of 2010.

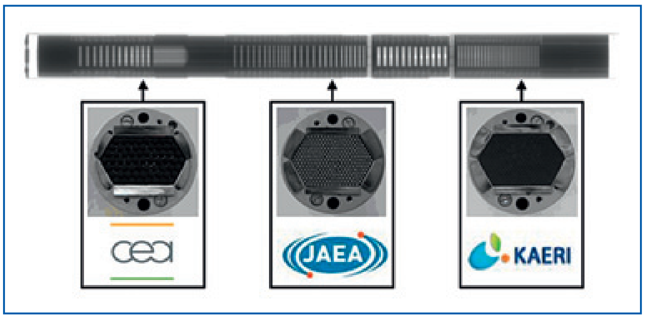


Figure 24 - Overview of the PYCASSO-II experiment by means of X-ray, and the samples provided by contributors from Europe (CEA, France), Japan (JAEA) and South Korea (KAERI)

PARTICLE SIZE ASSESSMENT IN ODS STEELS USING SMALL ANGLE NEUTRON SCATTERING

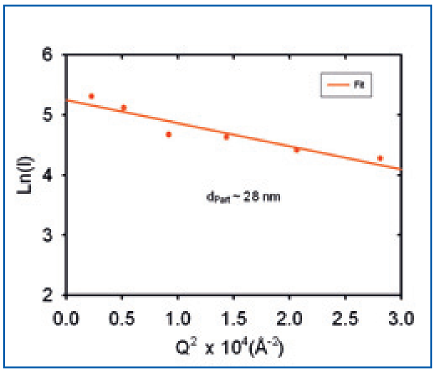


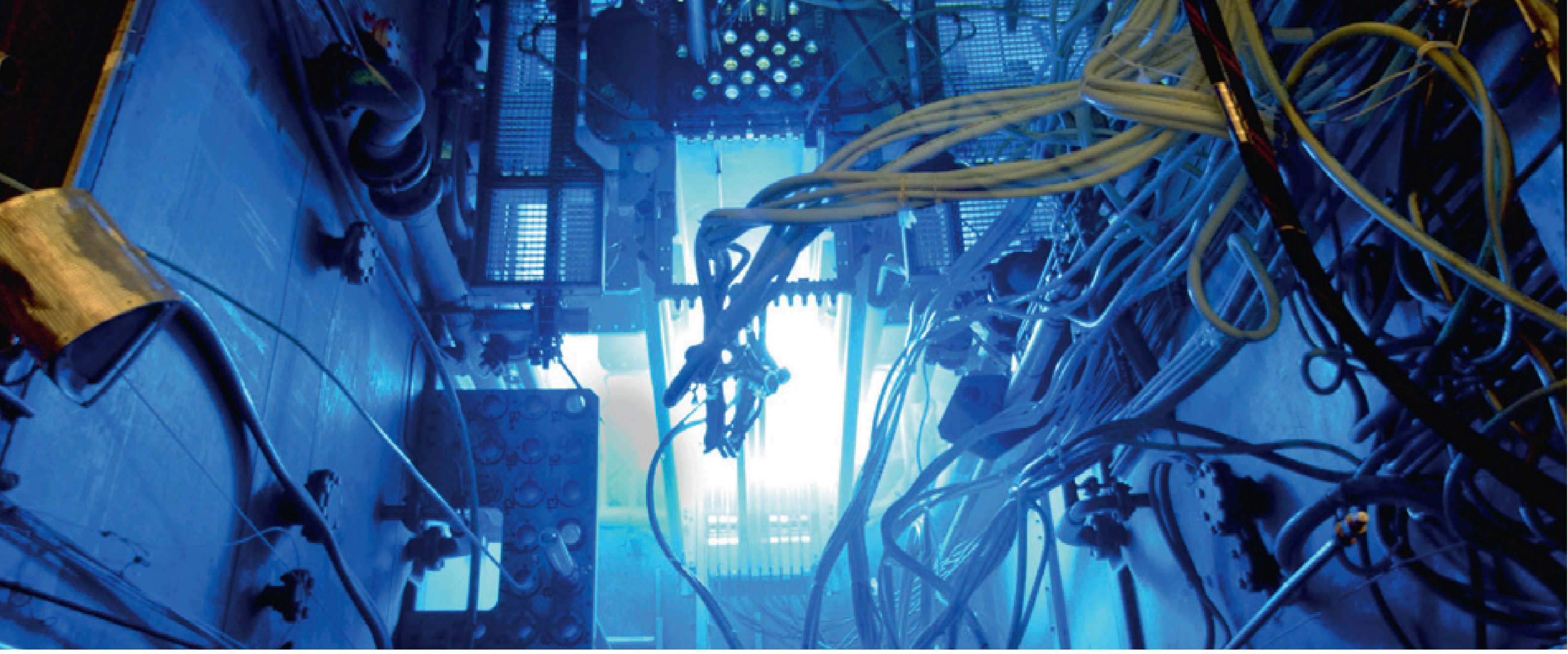
Figure 25 - Guinier plot for the assessment of the average particle size in an ODS Steel type PM2000 by SANS

Objective

Oxide Dispersion Strenghtened (ODS) Steels are among the candidate materials for use in future generation nuclear power systems. The structural and fuel cladding materials in GEN IV systems are confronted with more aggressive environments than in current light water reactors. This concerns thermal loading, corrosive behaviour of the primary coolant, neutron dose or their synergetic effect. Small Angle Neutron Scattering (SANS) is a method for analysing material inhomogeneities in the 1-1000 Å scale. The scattering data furnishes information concerning size and size distributions of inhomogenities within materials. It can therefore be used to study effects of thermal and/or irradiation ageing in ODS, duplex or Cr rich ferritic steels.

Achievements 2009

In 2009, the SANS facility at the HFR has been used to collect scattering data from coarse grained ODS steels of grades MA6000, MA956, MA957 and PM2000. Figure 25shows a Guinier plot derived from SANS data taken from a slice of PM2000 material. The analysis suggests an average size of embedded oxide nanoparticles of around 28 nm. The calculated mean particle size is in good agreement with observations made on this material by Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM).



HTR CORE STRUCTURES: GRAPHITE IRRADIATIONS

Objective

Graphite is a suitable material to be used as a neutron moderator and reflector in nuclear reactors. Due to its excellent high temperature performance, graphite is used as a structural material in the HTR design (High Temperature Reactor). The European Commission is supporting research projects (RAPHAEL-IP) for the development of HTR technology with the aim to create the technological requirements for designing and constructing an HTR in Europe. To achieve this, new nuclear graphite grades need to be developed and qualified, as the previously used grades are not available anymore. The properties of graphite are changing significantly and non-linearly under neutron irradiation. Therefore the graphite properties need to be obtained at different neutron dose levels. The property curves at two irradiation temperatures, 750°C and 950°C, are produced in four irradiation experiments conducted by NRG at the HFR. A crucial part of the programme is the possibility to reload irradiated (and therefore radioactive) graphite samples in new experiments to be able to measure the properties at different dose levels. This requires being able to build the experiments in a shielded environment, i.e. a hot-cell.

Achievements 2009

In 2009, the experiments INNOGRAPH 1b and INNOGRAPH 2b, loaded with irradiated material from the previous experiments, have been further irradiated. The experiment at 950°C started in 2008, with samples previously irradiated up to 7 dpa (displacements per atom). An extra dose of 6 dpa is targeted, leading to a cumulative dose in these samples of 13 dpa, to be achieved early 2010.

The experiment at 750°C, which started in 2007, is still in the HFR. This experiment will be completed by early 2010, after achieving an even higher dose of 23 dpa.

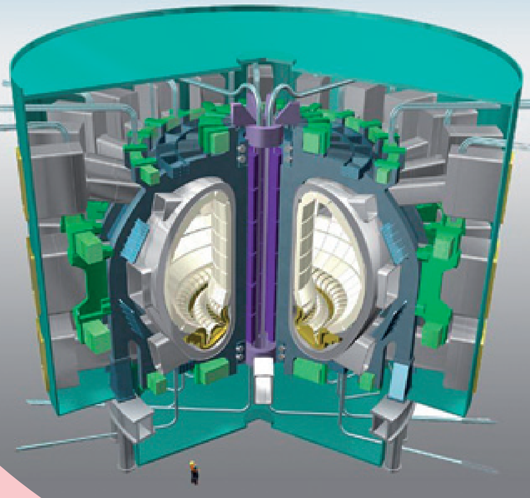
BLACKSTONE IRRADIATIONS: INVESTIGATION OF AGR LIFETIME EXTENSION

Objective

The UK has a fleet of Advanced Gas Cooled Reactors (AGRs) operated by British Energy. In order to extend the lifetime of the AGRs, graphite data at high dose and weight loss are required. These data allow the prediction and assessment of the behaviour of AGR graphite cores beyond their currently estimated lifetimes. Graphite degradation is indeed considered to be one of the key issues that will determine the remaining life of the AGRs. The BLACKSTONE irradiations use samples trepanned from AGR core graphite and subject them to accelerated degradation in the HFR. The results are designed to enable the future condition of the AGR graphite to be predicted with confidence.

Achievements 2009:

The BLACKSTONE irradiations started in the first cycle after the HFR stop due to the BPL problem. The BLACKSTONE capsules will continue into 2010 to achieve an irradiation dose of approx. 7 dpa.



Fusion Reactor Technology

The HFR irradiation capabilities are used for screening and qualifying fusion materials, components and technology. The HFR contributes to fusion technology development by simulating ITER and DEMO conditions in terms of irradiation temperature and neutron load. Furthermore, the hot cell laboratories perform post-irradiation testing, subsequently providing experimental results on neutron irradiated materials. The main areas of interest are the ITER vacuum vessel, the development of high heat flux components and blanket structures, and the development of the reduced activation materials such as 9Cr steels and innovative materials such as fibre reinforced composites. In addition, irradiation behaviour of ITER diagnostic instrumentation and the in-vessel parts of heating systems, which require dedicated assessment and testing programmes, are of great interest. As part of the qualification of materials supporting the licensing of a future reactor, the design of the International Fusion Materials Irradiation Facility (IFMIF) is under development. The HFR provides ample opportunity to qualify specific materials for the IFMIF target section, instrumentation and mock-ups. Presentations on ITER and DEMO development and qualification activities and the role of HFR in these activities have been delivered at the regular Fusion Symposia and Conferences.

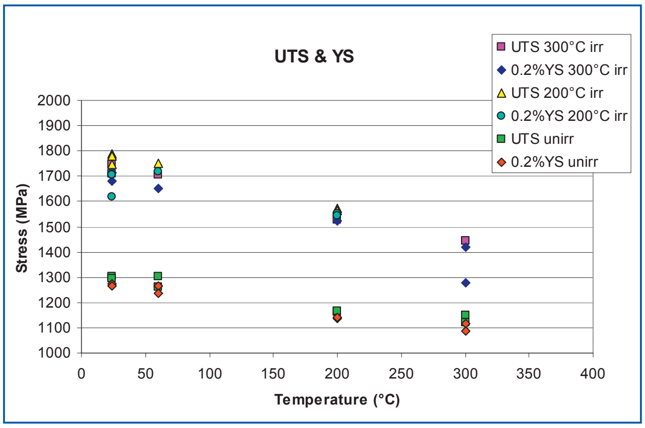


Figure 26 - Ultimate tensile strength and yield strength of unirradiated and irradiated PH13-Mo steel

ITER VESSEL/IN-VESSEL

In one of the European design concepts, the design of ITER first wall panels features PH13-8Mo steel as candidate material. After an irradiation campaign, the final report on the Post Irradiation Examination (PIE) of PH13-8Mo has been completed. This report is comprised of the results of the irradiation response up to 2 dpa in terms of yield stress hardening, elastic fatigue resistance and fatigue crack propagation.

Furthermore, a new test facility, called POSITIFE, for the irradiation of ITER primary wall modules is under construction. This facility will allow close simulations of thermal fatigue and simultaneous neutron loading in the HFR Pool Side Facility (PSF). The manufacturing of the components for this irradiation experiment started in 2009. The irradiation will start soon after the repair of the HFR in 2010.

NRG also developed with the Netherlands Organization for Applied Scientific Research (TNO) alternative manufacturing routes for thick tungsten claddings on copper-base substrates. Explosive forming of thick stainless steel sections was demonstrated by Exploform BV, in a joint effort with NRG and TNO to provide alternative manufacturing solutions for the ITER vacuum vessel. The experimental part of both projects on the cladding and the vessel were finished in 2008. Both final reports are now completed. The irradiation response of ODS-Eurofer97 steel at low and medium doses has been investigated by performing irradiation in the SUMO-11 and SUMO-12 experiments. The PIE of the ODS Eurofer97 has been completed in 2009. The final report is expected in 2010.

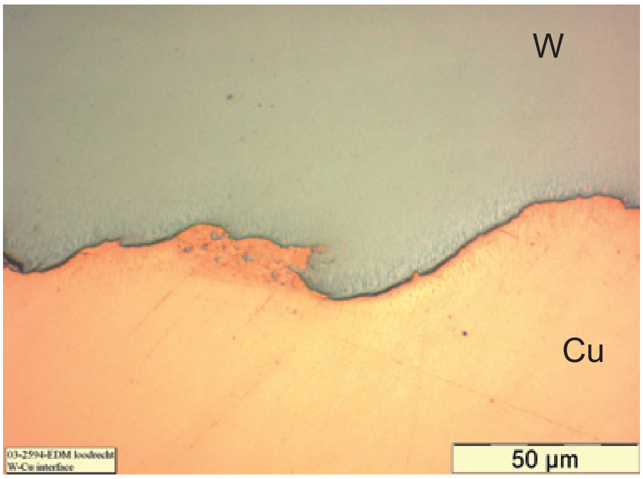


Figure 27 - Interface between W and Cu obtained by explosive cladding

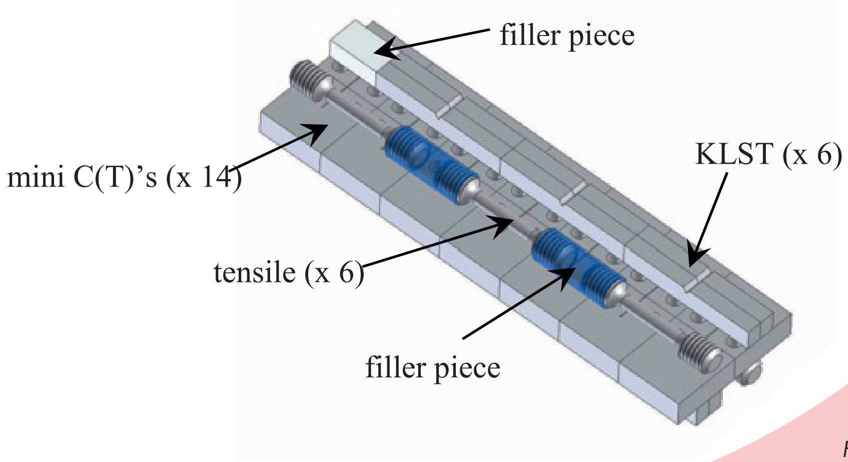


Figure 28 - Typical specimen stack in SUMO

HIDOBE EXPERIMENTS: BERYLLIUM FOR FUSION

Objective

The two objectives of the HIDOBE (HIgh DOse BEryllium irradiation) project are (i) to quantify the long-term behaviour (in terms of swelling, creep and tritium retention for fusion applications) of beryllium under irradiation conditions and (ii) to validate models for the thermo-mechanical behaviour of beryllium under irradiation conditions and tritium kinetics in beryllium. Various grades of beryllium (in pebble and pellet form) and titanium beryllides are irradiated in the HFR for 2 and 4-year periods, in two separate experimental setups (HIDOBE-01 and 02). In the framework of the IEA agreement on Radiation Damage Effects in Fusion Materials, partners in the EU, Japan and the Russian Federation provided these different grades of beryllium specimens. The experiment contained a few piggy-backs of ceramic breeder pebbles, complementary to the shielded HICU case.

Achievements 2009

Irradiation of HIDOBE-01 has been completed in 2008, with achieving its target dose of 3,000 appm helium. The dismantling has been successfully carried out in 2009 and up to 85% of the samples have been recovered without problems. Preparations for an extensive PIE campaign have been finished in 2009 and PIE will begin in 2010.

The HIDOBE-02 irradiation will continue in 2010, after repair of the BPL, to accumulate a total dose of 6000 appm helium production in beryllium and is expected to finish irradiation in the second quarter of 2011.

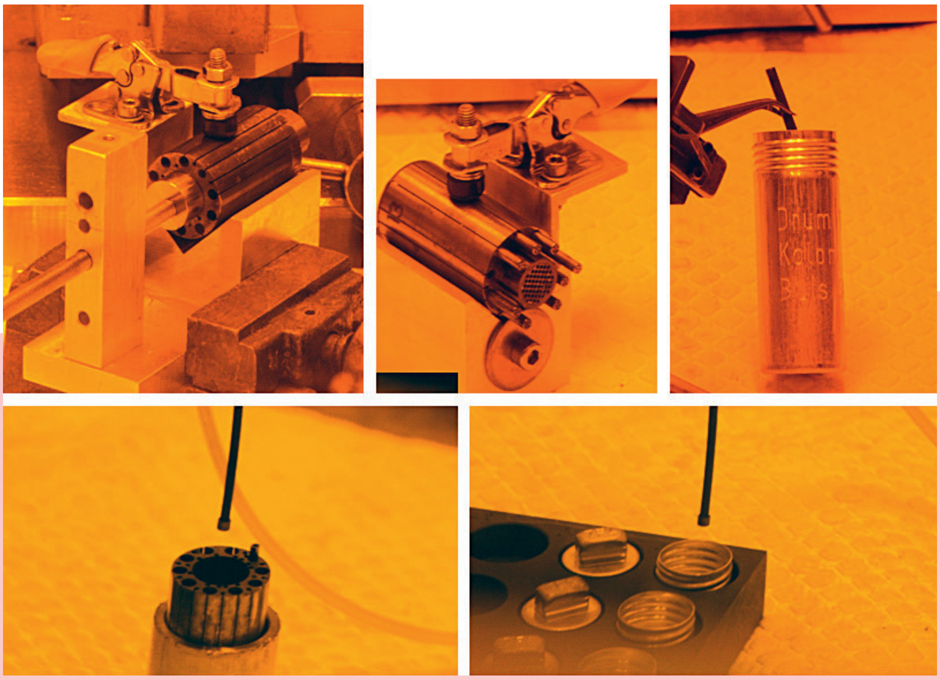


Figure 29 - Impression of the dismantling of HIDOBE-01. Upper right pictures show the retrieval of loose pebble from pebble stacks. The lower pictures show the retrieval of pellets with a dedicated 'suction cup' device.

Figure 30 - Specimens loaded in EXTREMAT

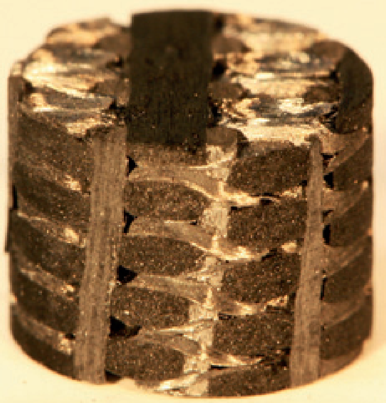


Figure 31 - Composite after irradiation in EXTREMAT

EXTREMAT: MATERIALS FOR EXTREME ENVIRONMENT (FISSION & FUSION)

Within various subprojects of the ExtreMat Integrated Project, a large number of materials were developed for use in extreme environments. Their stability under neutron load is investigated by irradiations in the HFR. To this aim, two irradiation capsules have been designed: A high neutron dose capsule (equivalent neutron dose in stainless steel of 5 dpa) in which specimens are irradiated at temperatures of 600°C and 900°C and a low neutron dose capsule, designed to reach a neutron dose of 0.7 dpa, at temperatures of 300°C and 550°C.
Irradiation of both capsules started in 2008 and finished in 2009. Afterwards, the low dose capsule was dismantled and the PIE started and will continue into 2010. The PIE includes measurements of physical properties such as thermal conductivity, thermal expansion and dynamic Young's modulus and mechanical properties such as tensile and flexural strength.

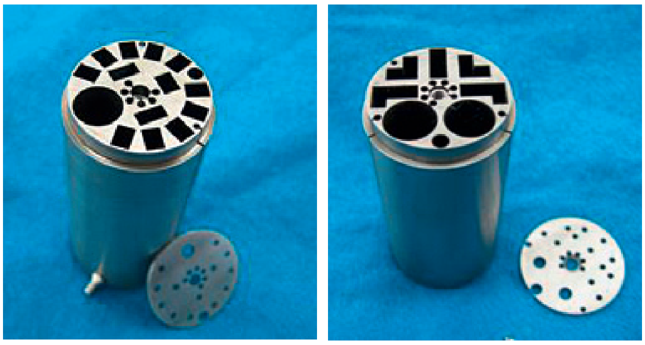


Figure 32 - Drums of EXTREMAT irradiation capsules

ADS MATERIAL DEVELOPMENT

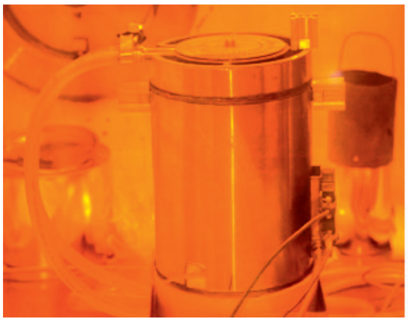
Objectives

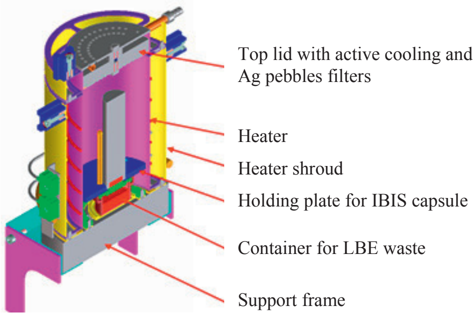
An experimental Accelerator Driven System (ADS) for the transmutation of Actinides is under development in Europe. It features Liquid Lead Bismuth Eutectic (LBE) as reactor coolant. Lead Bismuth has a low melting point (135 ˚C), but has corrosive properties to structural materials and welds. In addition, transmutation of Bi to the high radiotoxic ^{210}Po is a safety issue in the design of the ADS. Materials R&D is needed to test the corrosion behaviour of T91, 316L and weld specimens during irradiation in contact with LBE, and to examine the deposition of ^{210}Po in the irradiation containers and on the specimens after irradiation.

Achievements 2009

The irradiation of the two capsules was completed after the first three cycles of 2009. Due to the HFR core loading, the IBIS experiment was moved from position G7 to H6 for the last cycle. Also there, the target temperatures of 300 and 500°C were achieved. IBIS has been irradiated in the HFR for 250 Full Power Days in total, to an irradiation dose ranging from 1 (lower temperature) to 2 dpa (high temperature capsule).
During 2009, the facility for specimen retrieval was commissioned and built in the Hot Cell Laboratory. The Fuel Cell line of the HCL was selected because of the presence of alpha emitting radionuclide ^{210}Po. To assess the risk on handling ^{210}Po, a HAZOP study was performed, which formed the basis of the workplan for the retrieval of specimens. The procedure on the retrieval was performed on a container loaded with specimens and LBE that was not irradiated. Almost no wetting of the LBE on the specimens was observed. A dedicated tensile machine was also installed in this cell to test the irradiated specimens. The tensile specimens have showed no effects of the cyclic heating to 300°C in LBE on the elongation and the ultimate tensile strength.

Figure 33 - Retrieval set-up for specimens irradiated in IBIS, located in the F1 cell in the Hot Cell Laboratory.





Isotope Production

The year 2009 was again a year of high contrast. It started with the HFR being first out of operation, then operated only when justified by medical necessity and finally operated during the second half of 2009 at absolute maximum medical isotope production capacity.

The HFR entered into operation in mid-February 2009, when it was allowed to operate, only upon request, for medical isotopes production. This was imposed by the lack of alternative supply options in Europe and elsewhere in the world. This process required that each operating cycle was individually justified and approved by the Dutch Government, leading to a series of discontinuous cycles of different operational length. These variations in operation reflect the non-availability of other reactors in the European supply network. Over this period, the HFR ran at relatively high medical isotope production levels, to palliate limited alternative supply options.

In mid-May 2009, the NRU Reactor in Canada unexpectedly went out of operation due to the identification of a heavy water leak. It remained out of operation for the rest of 2009, triggering a continuous worldwide medical isotope shortage. The response of NRG was to reconfigure the production facilities and operating priorities of the HFR to allow the absolute maximum production levels of key medical isotopes (in particular the production of Molybdenum-99 for Tc-99m Generators). These changes were successfully implemented within 2 weeks after the notification of the NRU problem and Mo-99 production capacity was increased to a level around 180% of normal production. The reconfiguration allowed as many as 11 Mo-99 production irradiations to be performed in parallel and at times the HFR production exceeded the radiochemical processing capacity available within the European supply network. It was estimated that during this period the HFR produced enough material to allow more than 50,000 patient scans per day to be performed worldwide. This represented around 60% of the normal total world demand.

The extreme focus on medical isotope production was extended to all other medical isotopes which were produced in large quantities. This had unfortunately negative effects upon industrial isotope production and in particular on the newly developed business of the irradiation of Silicon Ingots to produce Neutron Transmutation Doped (NTP) Silicon for use in high voltage and other specialist electronic applications. Production of NTP Silicon was suspended until further notice, but it is anticipated that irradiations for this market will be reintroduced during the course of 2010.

During the year, NRG worked closely with other reactors in the medical isotope supply network, the Radiopharmaceutical Companies, the Medical Community, Governmental Departments and international organizations such as the OECD/NEA and the IAEA. These actions aimed at maximizing coordination and cooperation and as a result minimizing the effects of shortages whenever possible. Once again, the year 2009 fully underlined the critical role performed by the HFR and the supporting infrastructure within NRG to ensure the worldwide continuous and smooth supply of isotopes for essential medical services.

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

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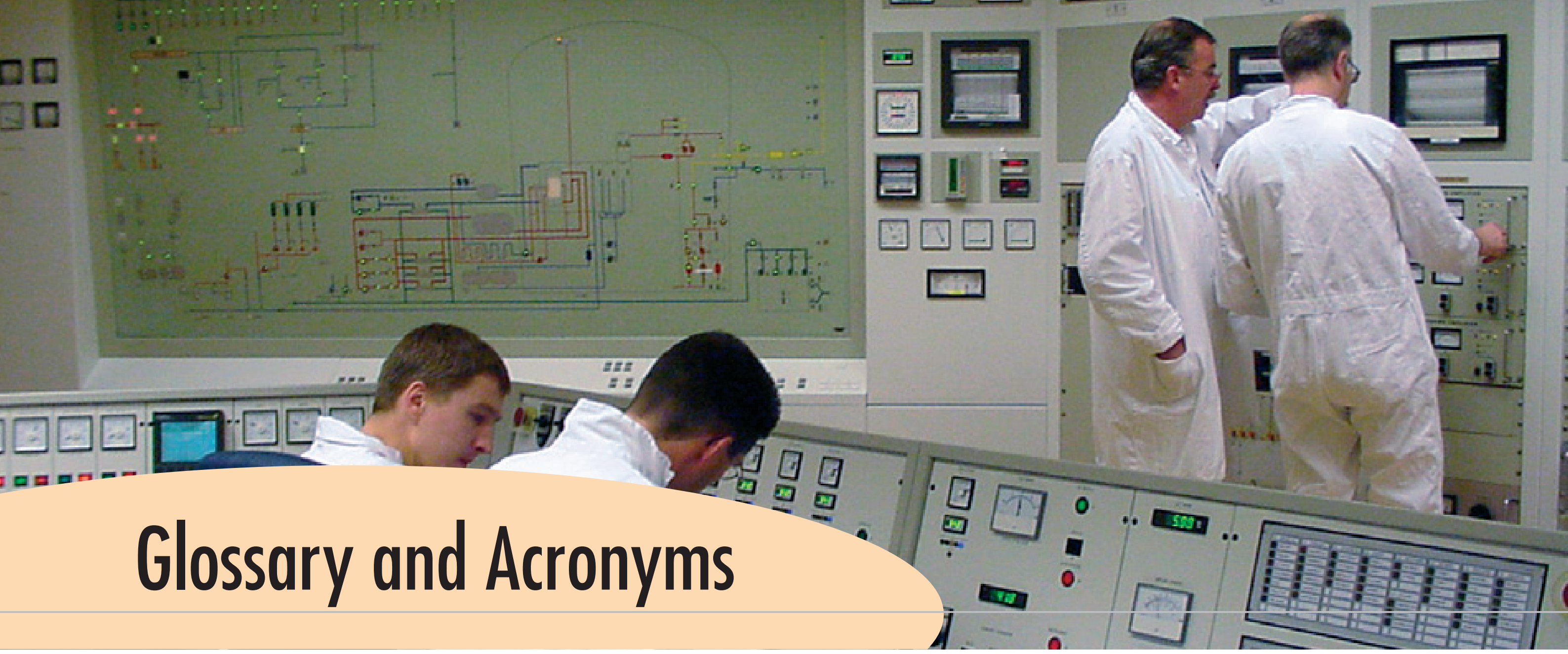

Glossary and Acronyms

ADS	Accelerator Driven Systems
APPM	atomic parts per million
CEA	Commissariat à l'Energie Atomique
COVRA	Centrale Organisatie Voor Radioactief Afval
DEMO	Demonstration Fusion Reactor
DG	Directorate General
dpa	displacements per atom
EC	European Commission
ECN	Energieonderzoek Centrum Nederland
EU	European Union
EUROTRANS	European Transmutation
FAIRFUELS	Fabrication, Irradiation and Reprocessing of FUELS and target for transmutation
FIMA	Fission per Initial Metal Atoms
FLUX	Fluence Rate
FP or FWP	Framework programme
GIF	Generation IV International Forum
HABOG	Interim storage centre for high level waste
HAZOP	A Hazard and Operability Study
HB	Horizontal Beam Tube
HCL	Hot Cell Laboratories
HELIOS	Helium in Oxide Structure
HEU	High Enriched Uranium
HFR	High Flux Reactor
HICU	High-fluence Irradiation of breeder Ceramics
HIDOBE	High Dose Beryllium Irradiation Rig
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IE	JRC Institute for Energy, Petten (NL)
IEA	International Energy Agency
INCOMODO	In-core Molybdenum Production Facility
ISI	In-Service Inspection
ITER	International Thermonuclear Experimental Reactor
JAEA	Japan Atomic Energy Agency
JRC	Joint Research Centre
KAERI	Korea Atomic Energy Research Institute
LBE	Lead Bismuth Eutectic
LEU	Low Enriched Uranium
MARIOS	Minor Actinides in Sodium-cooled Fast Reactors
NeT	Network on Neutron Techniques Standardisation for Structural Integrity
NRG	Nuclear Research and consultancy Group
PBA	Pebble Bed Assemblies
PBMR	Pebble Bed Modular Reactor
POSITIFE	Project Pool Side facility Thermally Induced Fatigue
PROMETEO	Production of Molybdenum by Fissile Target Irradiations
PSF	Pool Side Facility
PYCASSO	PYcarbon irradiation Creep and Swelling/Shrinking of Objects
R&D	Research and Development
RAPHAEL	Reactor for Process Heat and Electricity
RTD	Research and Technological Development
SANS	Small Angle Neutron Scattering
SUMO	In-Sodium Steel Mixed Specimens Irradiation
TG	Task Group
TN	Technology Network
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Scientific Research)
TRIO	Irradiation device with three Thimbles
TYCOMO	TYCO Molybdenum

European Commission

EUR 24513 EN - DG JRC - Institute for Energy
Operation and Utilisation of the High Flux Reactor
Annual Report 2009
Edited by: R. Moss, A. Marmier, P. Zamojski, R. May
Luxembourg: Publications Office of the European Union
2010 - 20 pp. - 21 x 29.7 cm
Scientific and Technical Research Series

ISSN 1018-5593
ISSN 1830-5997
DOI 10.2790/23845
ISBN 978-92-79-16579-5

Abstract

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

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

LD-NA-24513-EN-C

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ISBN 978-92-79-16579-5

Publications Office