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Operation and Utilisation of the High Flux Reactor

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HFR operation

Operating schedule

Due to the foreseen repair of the High Flux Reactor (HFR) primary cooling system (Bottom Plug Liner – BPL) in 2010, the operation cycles of the HFR could not be planned in advance. At the beginning of the year, the HFR was in operation for cycle 2009-10 which consisted of a scheduled number of 14.3 operation days. Cycle 2010-01 was planned before the BPL repair and consisted of a scheduled number of 31.7 operation days. The BPL repair started on February 20th 2010 in parallel to the periodic In-Service Inspection, several safety related modifications and the yearly containment leak test. After the successful BPL repair, the reactor started on September 5th 2010 with several tests and HFR's operators training obligations. A new cycle pattern was prepared consisting of a scheduled total number of 102 operation days. The target was to ensure the availability of sufficient irradiation capacity till the end of 2010. The HFR has therefore been in operation in 2010 for a total of 146 days (*Figure 1*).

Nominal power has been 45 MW (standard operating power), with a total energy production of approximately 6577.9 MWd, corresponding to a fuel consumption of about 8.2 kg ^{235}U. Cycle 2010-01 started nearly one and half hours earlier then planned, cycle 2010-02 was started nearly two and a half hours earlier, while cycle 2010-03 was started nearly seventeen and half hours later and stopped 20 minutes later then originally planned. This extra time was needed for experimental requirements. Cycle 2010-04 was started nearly fourteen hours later then originally planned. This extra time was needed to install new in-core beryllium reflector elements. Flux measurement at the reactor power of 500 kW in support of the HFR conversion program has been carried out during cycle 2010-04. After the scheduled end of operation of each cycle, the shut-downs included activities performed in the framework of the regular HFR's operators training. The detailed operating characteristics for 2010 are given in *Table 1*.

All details on power interruptions and power disturbances, which occurred in 2010, are given in Table 2. It shows that nine automatic reactor shut-downs (scrams), two manual reactor shut-downs, one manual power decrease and one automatic power decrease occurred (see also figure 2). Two of these scrams were due to human intervention (human error) and the remaining scrams were due to intervention by the safety systems of the reactor instrumentation devices.

Maintenance activities

In 2010 the maintenance activities consisted of the preventive, corrective and break down maintenance of all Systems, Structures and Components (SSC's) of the HFR as described in the annual and long term maintenance plans. These activities are executed with the objective to enable the safe and reliable operation of the HFR and to prevent inadvertent scrams caused by insufficient maintenance. Also the periodic leak test as one of the license requirements (0.2 bars overpressure - 24 hours duration) and the extended In Service Inspection including the measurements of the bottom plug liner were successfully performed. As part of the HFR Modification Plan several modifications were performed. All modifications were implemented after the revision of the plant description and operating instructions and following successful commissioning and testing.

Table 1: 2010 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)**
2010		**MWd**	**hrs**	**h.min**	**h.min**	**h.min**	**h.min**	**h.min**	**h.min**	**PD**	**Scram**	**Bq x E+11**
01.01 – 15.01	09.10	689.17	344	00.42	343.10		343.52	16.00	0.08		1	4.3
16.01 – 19.02	10.01	1424.77	760	02.10	759.17		761.27	78.33				5.4
20.02 – 08.09		BPL repair and maintenance period				20.36		4803.24				
09.09 – 08.10	10.02	1207.93	688	05.15	640.06		645.21	29.34	45.05		10	5.3
09.10 – 12.11	10.03	1391.70	760	02.40	741.19		743.59	79.40	17.21	2		4.2
13.11 – 17.12	10.04	1351.25	736	01.55	719.50		721.45	104.00	14.15			3.7
18.12 – 31.12	11.01	513.07	274	01.57	274.01		275.58	60.02				6.0
TOTAL :		6577.89	3562	14.39	3477.43	20.36	3512.58	5171.13	76.49	2	11	42.0
Percentage of total time in 2010 (8760 h) :				0.17	39.70	0.24	40.10	59.03	0.88			
Percentage of planned oper. time (3562 h) :				0.41	97.63	0.58	98.62					

Table 2: 2010 full power interruptions of HFR

DATE	CYCLE	TIME OF ACTION	RESTART OR POWER IN-CREASE	NOMINAL/ ORIGINAL POWER	ELAPSED TIME TO		DISTURBANCE CODE				REACTOR SYSTEM OR EXPERIMENT CODE	COMMENTS
					RESTART OR POWER INCREASE	NOMINAL/ ORIGINAL POWER	1	MW	2	3		
2010		hour	hour	hour	h.min	h.min						
13 Jan	09.10	09.17	09.25	10.07	00.08	00.21	MS	0	A	R	Secondary system	The reactor was manually shut-down preventively; due to ice crust forming in the NH-channel, not enough cooling water was available.
09 Sept	10.02	17.42	17.46	17.52	00.04	00.10	AS	0	R	I	Primary system	Primary flow <90% caused a reactor scram.
09 Sept	10.02	20.47	20.51	21.02	00.04	00.15	AS	0	R	I	Primary system	Scram on primary flow <90% without any signal on ann. AM-02. Reactor restarted after the primary pressure and flow was checked.
10 Sep	10.02	00.56	00.59	01.13	00.03	00.17	AS	0	P	I	Exp 292-01	Cool water pressure too low of experiment TIRO-1 caused a reactor scram.
16 Sep	10.02	16.12	16.21	16.43	00.09	00.31	AS	0	P	M	Exp. 354-02	Cool water pressure too high of experiment TYCOMO-2 caused a reactor scram.
17 Sep	10.02	09.13	09.18	09.48	00.05	00.35	AS	0	P	H	Exp. 354-02	By mistake the wrong cool water flow controller readjusted leading to a reactor scram.
23 Sep	10.02	16.18	16.24	16.57	00.06	00.39	AS	0	P	M	Exp. 354-01	The cool water hose of experiment TYCOMO-1 slipped off and caused a reactor scram.

24 Sep	10.02	08.00					MS	0	P	R	Exp. 354-01 and 354-02	To renew the cool water hoses of the experiments TYCOMO I and 2 the reactor was manually shut-down.
26 Sep	10.02		12.24	13.11	28.24	29.11						
26 Sep	10.02	19.44	19.48	20.17	00.04	00.33	AS	0	P	I	Exp. 292-01	Due to manipulations with experiment TIRO-1 the cool water pressure dropped leading to a reactor scram.
07 Oct	10.02	13.32	13.38	13.52	00.06	00.20	AS	0	R	I	Instrumentation	No annunciator came up, but supposed that instrumentation fault caused a reactor scram.
12 Oct	10.03	12.34		12.54		00.20	MP	30	E	R	Exp. 333-01	Unexpected temperature rise in experiment HICU 333-01 was checked.
17 Oct	10.03	14.32		15.01		00.29	AP	10	A	E	Ventilation system	Reactor hall ventilation system switched off automatically with an automatic power decrease as result.
21 Oct	10.03	15.53	15.57	16.09	00.04	00.12	AS	0	R	H	Reactor interlock	Wrong switch activated of the reactor interlock with a reactor scram as result.

1. LEADING TO		2. RELATED TO		3. CAUSE	
- automatic shut-down	AS	- reactor	R	- scheduled	S
- manual shut-down	MS	- experiment	E	- requirements	R
- automatic power decrease	AP	- auxiliary system	A	- instrumentation	I
- manual power decrease	MP	- Production facility	P	- mechanical	M
				- electrical	E
				- human	H

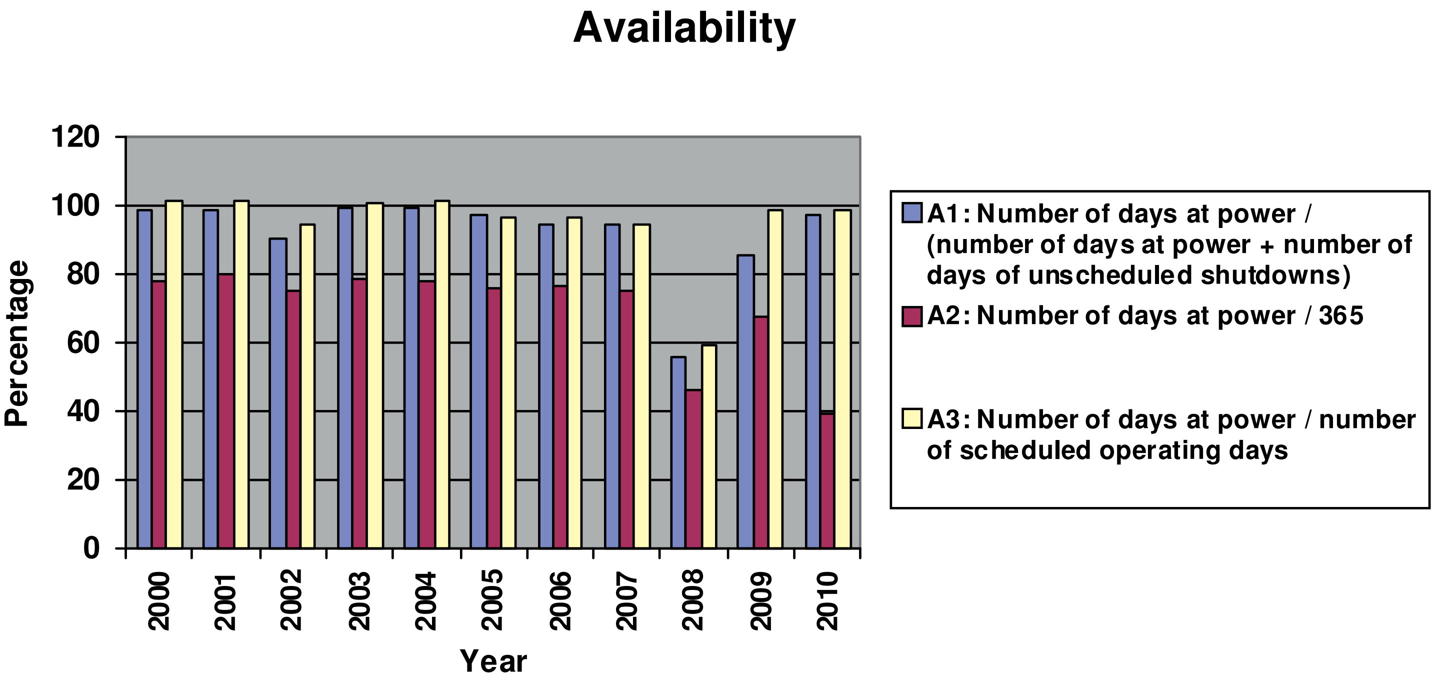

Figure 1: HFR availability

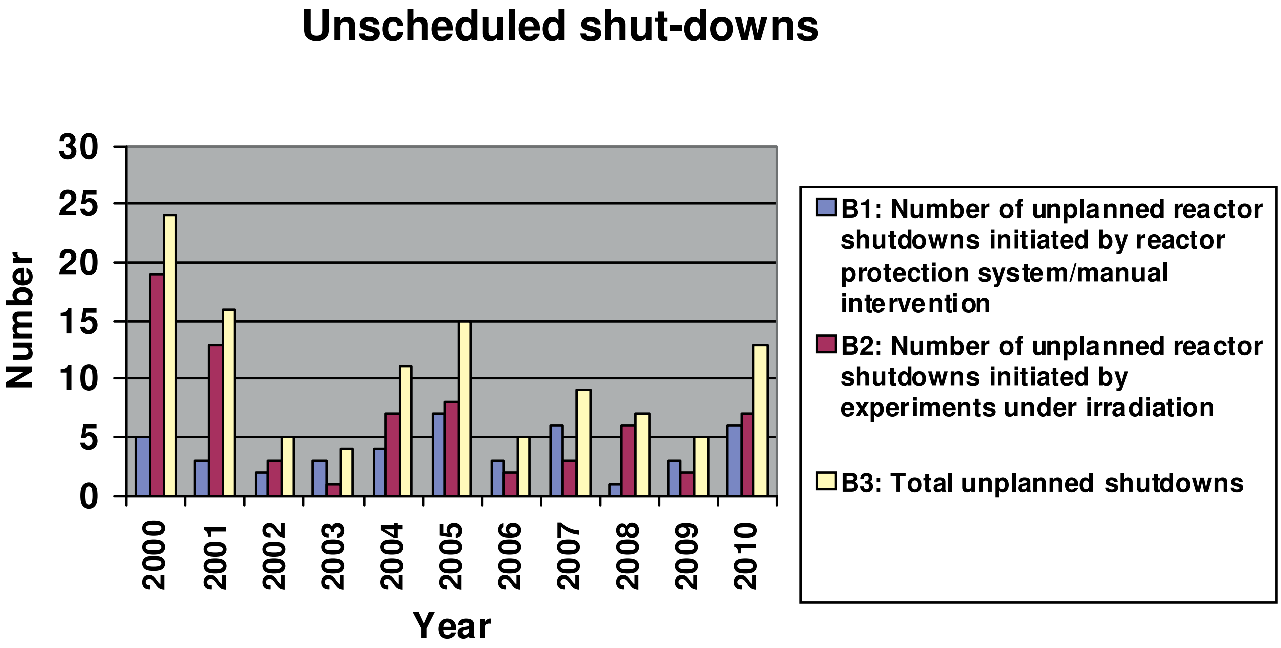

Figure 2: HFR unscheduled shutdowns

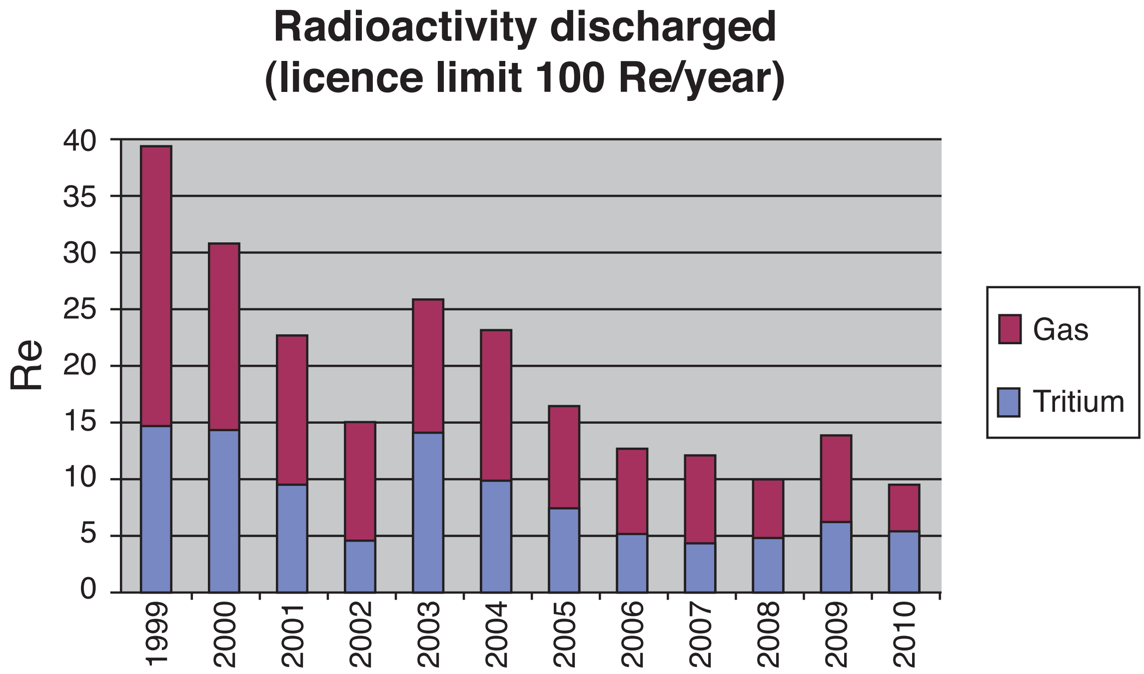

Figure 3: Radioactivity discharge for 1999-2010

Repair of the HFR primary coolant system

The HFR reactor vessel is located in a concrete pool with floor and walls some meters thick, lined with aluminium. For cooling and radiation protection purposes the pool is filled with water (approximately 9 meters deep); the top of the pool is open to enable loading and unloading of fuel and experimental rigs. Two sections of the reactor primary coolant system are embedded in the concrete at the bottom of the reactor pool. These parts are conical in shape and usually identified as "reducers". During the In Service Inspection (ISI) performed in the summer of 2005, some deformations were detected in two parts of the section of reactor's primary cooling water system embedded in concrete. Investigations were immediately started to analyse the cause of the deformations and to determine their possible impact on the safety and reliability of the HFR. The frequency of the periodic inspections of both the reducers and the deformations was also increased.

The deformations were thought to derive from a galvanic corrosion process (due to a combination of carbon steel, moisture and aluminium) causing a decrease of the reducer's aluminium wall thickness and expansion of the corrosion product (having a volume 2 to 3 times greater than that of aluminium), pushing the reducer wall inwards. From 2005 onwards, additional investigations were executed, allowing for accurate measuring of the deformation and of the residual material thickness. In August 2008 a gas bubble jet was detected, released in the primary water from one of the deformations. The gas bubble jet appeared to emerge at a frequency of once every 10 – 20 minutes and lasted 10 to 30 seconds each time. The reactor could still be put in operation on the basis of a temporary license granted by the Dutch regulator, based on three conditions:

- That the HFR would only operate when necessary for medical needs (no alternatives available to ensure supply of medical radioisotopes);
- That in case any water leakage from a reducer was detected, the HFR would be immediately shut down;
- That the works for a final repair of the reducers would start at the latest on March 1st, 2010.

The final repair required setting up a dedicated project organisation by appointing an experienced project manager and a project team selected on the basis of specific expertise, including external experts. The project objective was to safely repair or replace the two reducers by gaining access through the concrete ceiling of the sub pile room, the space directly under the reactor vessel.

A major decision in the project was to drain the reactor pool at an early stage of the work for the safety of the workers. Although calculations indicated that the pool bottom would be strong enough to contain the full amount of water after removal of the concrete from the cavities, the pool was nonetheless drained in order to exclude any risk of flooding in case of failure. This decision had far reaching consequences, since it required the installation of alternative radiation shielding material on the pool bottom (tungsten alloy with a density of 18 000 kg / m^3). Each step of the repair project was tested on a full scale mock-up. A replica of the entire section with one of the reducers helped to select the most efficient tools and procedures for the removal of the concrete and its restoration. This training involved workers who later had to perform the actual operation in a limited space of the sub pile room. The material used for replacing the removed concrete was supplied by a Swedish mine. It provided the same high density concrete filler (magnetite) which was used 50 years ago for the construction of the HFR.

The repair started on February 19th, 2010. After removing the reactor internals (fuel elements, control rods, isotope production rigs and experimental facilities) the radiation protection equipment inside the reactor and shielding blocks at the bottom of the reactor pool were installed in order to reduce overall radiation levels within the reactor building. After covering the pool top with the concrete slabs and draining the water, the radiation levels were measured. It became apparent that, although the shielding had reduced the radiation levels by the required order of magnitude, at some locations the levels were still too high. Additional shielding had therefore to be designed, made and fitted, which proved to be adequate. The concrete was removed using a hollow-drill-technique. Holes were cut of various lengths in the concrete around the reducer for a total length of more than the height of the Eiffel Tower. The last portion of concrete was removed by cutting with hand tools, to avoid damaging the reducers.

Inspections carried out after cleaning the reducers’ surface confirmed that the cause of the deformations was galvanic corrosion, initiated by the combination of steel, aluminium and moisture. The reactor pool has an aluminium liner which is designed in such a way, that when small amounts of pool water are released due to thermal movement, they are transported to a drain system through small channels in the concrete. Some of this moisture migrated through the concrete and reached the reducers. Inspections also showed that the reducer material outside the deformations areas was in a perfect condition. It was therefore decided to proceed with a local repair by removing the damaged material (a larger hole at the bottom and a smaller hole at the top of the reducers). All four holes were then closed by welding pre-fabricated plates of aluminium. The top plates were welded from within the reducers through the larger holes and then the bottom plates were welded from outside. After welding was completed, the cavities were filled with rebars and concrete. Finally, the reactor systems were submitted to extensive commissioning tests prior to reloading the core and starting-up the HFR on September 9th, 2010.

HFR as a Tool for 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. 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. About 35 organizations are actively participating in the work of NeT, including eight organizations from the new EU member states and three organizations from candidate countries

In 2010, because of the extended shutdown of the HFR, the NeT related experimental activities were restricted to small angle scattering studies of materials ageing processes, mainly in candidate materials for Generation IV nuclear reactors. The NeT Steering Committee met twice in 2010 to discuss the progress in the different Task Groups and to prepare the work of NeT for the future. Among the Technical Groups, TG1 is setting a benchmark for numerical and experimental work that will continue to be available to nuclear engineers for testing their methods in the future. With TG1, the first task Group of NeT coming to an end, a final report is in preparation.

Residual Stress Measurements by Neutron Diffraction at the HFR

Despite the extended shut-down of the HFR two series of investigations have been undertaken at the residual stress measurement facilities:

- Using the Large Component Neutron Diffraction Facility of beam tube HB4 (horizontal beam tube), a series of measurements was executed on a slice cut from a bi-metallic piping weld representative of a connection from a nuclear Reactor Pressure Vessel to its primary piping. These investigations were addressing measurement methodology with the aim to study the possibilities for obtaining improved measurement quality in inhomogeneous materials such as multi-pass fusion welds. The instrument capabilities at HB4, in particular the ability to rotate the specimen during measurement (rocking) were exploited in this context.
- At HB5, a series of feasibility measurements was performed on a thick walled stainless steel piping weld with a small inner diameter, representative of an application in the sodium cooled fast reactor. Such measurements were in principle found to be feasible, but the possibilities for the necessary specimen modifications remain to be established.

Microstructure evolution in high Cr-content oxide dispersion strengthened steels after thermal ageing using Small Angle Neutron Scattering

Ferritic Oxide Dispersion Strengthened (ODS) Steels are among the candidate materials for Generation IV nuclear reactors. While offering good high temperature creep strength, radiation resistance and oxidation resistance, they may suffer from hardening embrittlement, which is attributed to the phase separation into Fe-rich α and Cr-rich α' phases forming during thermal ageing of the material at intermediate temperatures. In order to promote their use, it is necessary to understand the evolution of their microstructure during thermal ageing. The effects of thermal aging at 475°C for 100, 500 and 1000 hours on the microstructure of the PM2000 and MA956 (Fe-Cr-Al) ODS steels have been investigated with small angle neutron scattering (SANS). The hardening during thermal ageing has been monitored by Vickers microhardness measurements.

All materials showed a strong SANS signal in both the as-recrystallised and the aged states. The SANS measurements revealed that thermal treatments result in substantial changes in the microstructure at the nanometer size scale. The analysis of the experimental results indicates changes in the size distribution of the scattering centres. During the heat treatment new scatterers with mean size of 2.5-3 nm were formed. Hardness was found to significantly increase as a function of ageing time. The hardening is related mainly to the formation of a Cr-rich α' phase.

CRYO Experiment: Alpha-Emitters Radiotoxicity Reduction

The JRC is conducting exploratory research dealing with the supposed reduction of the half-life of alpha decay isotopes embedded in a metallic matrix at cryogenic temperatures (4 kelvin). Eight discs of pure copper with some bismuth implanted, in order to obtain Polonium-210 (^{210}Po) which is a pure alpha emitter, have been irradiated to study the behaviour of the alpha emitter under cryogenic temperature. Eventually, the discovery of the acceleration of alpha decay emitter embedded in a metallic matrix at cryogenic temperature may ultimately provide an option for the reduction of the amount of nuclear waste. Some other research has been conducted about this subject and, by conducting this experiment, JRC would like to clarify, the status of these studies to avoid any possible speculation. Therefore, a new irradiation experiment called CRYO has been carried out in the HFR. The main objective of CRYO is produce Polonium-210 embedded in a copper matrix. ^{210}Po is a pure alpha emitter with a relatively low half-life (about 138 days) and will be produced by the transmutation of Bismuth-209 which has been deliberately implanted on eight discs of pure copper. The CRYO experiment was irradiated for 1 cycle (~29 full power days). The irradiation of CRYO took place between December 22nd, 2009 and January 15th, 2010. The samples have been shipped to the JRC Institute for Transuranium Elements for a series of post-irradiation examinations.

Fuel irradiations

HELIOS Fuel Experiment: Americium Transmutation

Americium is one of the radioactive elements that contribute to a large part of the radiotoxicity of spent fuels. Transmutation by irradiation in nuclear reactors of long-lived nuclides (like ^{241}Am) is, therefore, an option for the reduction of the mass and radiotoxicity of nuclear waste. The Helios experiment, as part of the FP6 EUROTRANS Integrated Project on Partitioning and Transmutation, 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 target 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 of such kind of fuel, a significant amount of helium is produced due to the nuclear transmutation of americium. The study of gas release is of vital importance to allow better performance of the U-free fuels. Two different approaches are followed to reach early helium release:

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

HELIOS, started on April 29, 2009 and has been successfully concluded on February 19, 2010 after ≈ 242 Equivalent Full Power Days (EFPD). The irradiation was flawless although it had to finish 1 cycle earlier due to the HFR repair. During irradiation, cladding temperatures were monitored, as well as the central temperatures in two HELIOS pins. After irradiation, the experiment underwent dismantling and PIE in the NRG Hot Cell Laboratory. In 2010 all non-destructive measurements have been performed on the 5 pins consisting of visual inspection, profilometry to measure dimensional changes of the cladding, and gamma scanning to look at the behaviour of fission products inside the pins.
Clear differences in behaviour were detected between the cold and warm pins consisting of the CerMet fuel with molybdenum matrix fuel. The colder pins showed relatively stable behaviour whereas in the profile of the warm pins the individual pellets indicated a clear swelling of the fuel pellets against the cladding. This result was not predicted by the modelling since the higher temperatures were expected to release the helium from the matrix more easily, reducing swelling at higher temperatures.

For 2011, preparations are being made for the destructive PIE campaign, including optical microscopy and SEM with WDS/EDS measurements.

MARIOS Fuel Irradiation: Minor Actinide Recycling

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. NRG and JRC-IE work closely on the HFR irradiations scheduled in FAIRFUELS. The MARIOS irradiation programme deals with heterogeneous recycling of Minor Actinides (MAs) in sodium-cooled fast reactors (i.e. the MA-bearing blanket concept). Minor Actinides, such as americium and curium, are long-lived elements in the high level waste, which are currently not recycled. The aim of MARIOS irradiation test is to investigate more closely the behaviour of minor actinide targets in an uranium oxide matrix carrier. In these targets, large amounts of helium are produced, which causes significant damage to the material under irradiation. For the first time americium (^{241}Am) is included in a (natural) uranium oxide matrix $Am_{0.15}U_{0.85}O_{1.94}$ to conduct an experiment in order to study the behaviour in terms of helium production and swelling.

The design of MARIOS was finalized in 2010 after the nuclear analyses and the thermo-mechanical analyses had been concluded. The fuel pellets, made by CEA in France, arrived in April 2010 and the capsules, filled with the fuel pellets, were prepared in Petten. The americium-containing samples were squeezed in between metal disks to ensure a flat and well-defined temperature profile. Four separate capsules were prepared. The sample holder for the experiment and the assembly of all elements were finalized in December 2010 and received the required approvals. The MARIOS irradiation will start the first quarter of 2011 and will last for approximately 300 full power days.

SPHERE

Within the FP7 FAIRFUELS project the irradiation test SPHERE was 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. Especially when dealing with highly radioactive minor actinides, dust-free fabrication processes are 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-type and Sphere-Pac-type, will be fabricated at JRC-ITU in Germany. These fuels will be irradiated at HFR in a dedicated test-facility. It will be the first irradiation test of this kind, as Minor Actinides bearing Sphere-Pac fuel has never been irradiated before. The SPHERE irradiation should start in at the end of 2011 / beginning of 2012 and will last for approximately 300 full power days. The preliminary design for the SPHERE irradiation test has been decided in 2010 and the fabrication of the fuel will start in 2011.

High Temperature Reactor Fuel Irradiations

Background

The High Temperature Reactor (HTR) is a gas-cooled graphite moderated nuclear reactor concept. The high temperature coolant output, effective fuel use, large R&D experience and its robust passive safety concept make it an attractive heat and power generating system. The HTR is specifically intended for deployment in an industrial environment. HTR fuel consists of TRISO-particles which are uranium oxide kernels coated by a porous graphite buffer layer and a pyrocarbon-siliconcarbide-pyrocarbon coating. 10,000-15,000 of these particles (1 mm diameter) are contained in a graphite matrix in the form of a 6 cm diameter fuel sphere (“pebble”) or in the form of finger-thick cylinders (“compacts”). In the past, several irradiation tests of low-enriched uranium fuel types in the HFR were carried out 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).

Preparation of HFR-EU1 has begun in summer 2002 as a collaborative effort between the European High Temperature Reactor Technology Network (HTR-TN) led by JRC and the Tsinghua University Beijing, China, Institute of Nuclear and New Energy Technology (INET) which runs the HTR-10 test reactor and which is involved in the construction of the demonstration plant HTR-PM. Historical and newly produced fuel should be irradiated to high burn-up and be compared under irradiation and during safety tests (KÜFA). KÜFA tests verify fission product retention of irradiated pebbles beyond 1600°C under simulated accident conditions. The combination of irradiation and KÜFA tests is a fuel safety qualification and licensing requirement for new fuel and enhances understanding of fission product release and failure mechanisms should coating failure occur.

Objectives

Like earlier experiments, HFR-EU1 had the objective of exploring the potential for high performance and high burn-up of the existing German AVR fuel pebbles and of newly produced fuel. During extensive irradiation tests at and above nominal power plant conditions in the 1980s and 1990s, fuel elements with LEU-TRISO coated particles performed very well, unless they were harshly driven beyond their design capabilities as this was done in the earlier HFR-EU1bis irradiation test (2004-2005). The irradiated pebbles were 60 mm in diameter with LEU-TRISO coated particles. The 3 German pebbles were of type AVR GLE-4 produced as batch AVR 21-2 in October 1987. They were manufactured by HOBEG. The 2 Chinese pebbles were produced by INET for the operation of the HTR-10 test reactor.

Achievements

HFR-EU1 was dedicated to conservative fuel temperatures (900 – 950°C measured at the surface) but high burn-up (9.3 – 14.3 %FIMA, to be confirmed by measurements). The experiment was connected to a new gas handling facility that enabled continuous fission gas release analysis by gamma spectrometry. The 5 pebbles were packed in a REFA-172 rig, which is a standard reusable device in the HFR. The sample holders (1st containment) are made of AISI 321 capsules containing several graphite cups holding the pebbles in place. The REFA-172 rig forms the 2nd containment. The upper sample holder (INET fuel) was equipped with 14 thermocouples, while the lower one (AVR fuel) had 20. Nuclear instrumentation included 12 neutron fluence detector sets, 4 self-powered neutron detectors and 4 gamma-scan wires.

The irradiation test was performed in two campaigns from 29 September 2006 to 24 February 2008 (12 reactor cycles of 28 days each) and continued from 19 October 2009 to 19 February 2010 (4 reactor cycles) achieving 445 efpd with a fast neutron fluence of approx. 4.95×1025 m-2 and achieving predicted burn-ups per pebble. The interruption of the test was imposed partly by reactor outage and partly by unexpectedly high thermocouple failure in the AVR capsule which required construction of a new safety case.

HFR-EU1 was conducted using a gas handling station, the so-called “Sweep Loop Facility” (SLF). The SLF was operated from a PLC controlled command cabinet, which also contained a number of alarm functions. This installation provided all containments with variable gas blends for temperature control and enabled permanent surveillance of containment integrity as well as gas sampling for fission gas release measurements by gamma spectrometry with the associated alarm functions. Gas sampling was in general performed once per week per capsule. For the last 4 cycles, a newly developed stand alone gamma spectrometry system was set up to provide an on-line, automatic data record.
Different Xe and Kr isotopes were measured, namely ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr, ^{135}Xe, ^{135}mXe, ^{137}Xe, ^{138}Xe and ^{133}Xe.

Together with the known gas flow, pressure and temperature, the fission gas release rate R from the two capsules could be determined and related to the birth rate B from neutronics calculations thus yielding the characteristic R/B value which is considered a good health indicator of coated particle fuel. Fission gas release from both fuel types was consistently low thus hinting at absence of fuel damage. The release over birth (R/B) value was approximately 7.2×10-8 for INET fuel and 2.5×10-7 for AVR in ^{85m}Kr at the end of the irradiation. These values hint at absence of particle failure and place both fuel types irradiated in HFR-EU1 among the good performers. The burn-up shown here is the one pre-calculated for the experiment (capsule averaged). Later adjustments will be made once the burn-up measurements of the pebbles and the analyses of gamma scan wires and fluence detectors are available. The error is expected to be in the 10% range, so that the positive conclusions from the test will not change.

The experiment was dismantled in the course of 2010. As part of the FP7 ARCHER Collaborative Project extensive PIE (at NRG Petten and JRC-ITU in Karlsruhe) and KÜFA tests will be performed starting in 2011.

Materials Irradiations

HTR Core Structures Graphites

Graphite is a suitable material to be used as a neutron moderator and reflector in nuclear reactors. Due to its excellent high temperature performance graphite is used as a structural material in the HTR design (High Temperature Reactor). The European Commission is supporting research projects (RAPHAEL-IP) for the development of HTR technology with the aim to create the technological requirements for designing and constructing an HTR in Europe. The qualification of nuclear graphite is key element to achieve these goals as the properties of graphite are changing significantly and non-linearly under neutron irradiation. Therefore the graphite properties need to be obtained at different neutron dose levels. NRG plays a leading role in the research of graphite irradiation behaviour for HTR technology. A large irradiation programme of various nuclear graphites took place in the HFR within the RAPHAEL project. The property curves at two irradiation temperatures, 750ºC and 950ºC, are produced in four irradiation experiments. Re-irradiation of the graphite was a crucial part of the irradiation programme and has shown to be very successful.

In 2010 the full irradiation programme was completed, including the higher dose irradiation experiment, up to 23 dpa and the experiment targeting 13 dpa. The dismantling of the experiments took place at the NRG hot cells. The agreed PIE programme was performed and the results of the graphite property changes were published at the international nuclear graphite specialist meeting.

Materials for FISSION & Fusion (EXTREMAT)

A large number of materials developed for use in extreme environments within the various subprojects of the ExtreMat Integrated Project are tested on their stability under neutron load in the High Flux Reactor. Two irradiation experiments have been designed to be irradiated at different temperatures and doses (600°C and 900°C, 5 dpa and 300°C and 550°C, 0.7 dpa) in order to simulate the expected real conditions. The Extremat I irradiation was performed successfully, while the Extremat II irradiation suffered from a severe heat leak due to the swelling of ceramic specimens and was ended prematurely. About half of the specimen drums from Extremat II can nonetheless be considered as having been irradiated at a single irradiation temperature. Specimens from those drums produce meaningful data. The Post Irradiation Examination took place in 2010. A large variety of materials were irradiated including (doped) graphites, SiC and C composites, tungsten alloys, 14Cr ODS steels, Rhenium, fibre-reinforced Cu and CuCrZr. The PIE included measurements of physical properties such as thermal conductivity, thermal expansion and dynamic Young's modulus and mechanical properties such as tensile and flexural strength. The outcome of the PIE will result in further development of the various materials and finally in the qualification for the real application.

BLACKSTONE irradiations

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 is required, to allow prediction and assessment of the behaviour of AGR graphite cores beyond their currently estimated lifetimes. Graphite degradation is considered to be one of the key issues that will determine the remaining life of the AGRs, thus materials property data at extended weight loss and dose is essential for continued safe operation and lifetime extension. The BLACKSTONE irradiations use samples trepanned from AGR core graphite and subject them to accelerated degradation in the high-flux test reactor. The results are designed to enable the future condition of the AGR graphite to be predicted with confidence.

The Blackstone irradiations were completed in 2010 after achieving the required weight loss and dose levels. In 2010 the dismantling of both BLACKSTONE experiments took place and the PIE started. In the meanwhile two new irradiations are being prepared to achieve even higher dose and weight loss. The objective of these experiments is to consolidate the database produced in phase I and to provide an extensive properties database for HRA/HYA graphite. These latter experiments are being prepared to start in 2011

Irradiations for Fusion Technology

The HFR capabilities are very much used for screening and qualifying fusion materials, components and technology. The HFR contributes to the fusion technology development by simulating ITER and DEMO conditions in terms of irradiation temperature and neutron load and subsequently providing experimental results on heavily neutron irradiated materials using the hot cell laboratories to perform the post-irradiation testing. The main areas of interest are the (ITER) vacuum vessel, the development of high heat flux components and blanket structures, along with 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 assessments 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.

An example of experiments prepared in 2010 is POSITIFE, which tests first wall mock-ups under simultaneous thermal cycling and neutron irradiation.

HIDOBE

In the HIDOBE (*HIgh DOse irradiation of BEryllium*) experiment, various grades of constrained and unconstrained beryllium pebbles and titanium-beryllide samples are irradiated at high temperatures in the High Flux Reactor. High dose irradiation testing is necessary because the beryllium irradiation behaviour in fusion reactors, in particular its swelling and creep, has an impact on e.g. structural integrity of the breeder blanket and the tritium inventory and it is considered a critical issue for the HCPB concept for performance, safety and waste management.

The HIDOBE experiment consists of two separate rigs (HIDOBE-01 and HIDOBE-02), each loaded with 19 grades of beryllium and titanium beryllides, and have target fluences that are aimed to produce about 15% and 30% of the DEMO end-of life conditions (3000 and 6000 appm helium in beryllium, respectively).

HIDOBE-01 PIE

HIDOBE-01 has reached its irradiation target after two years of irradiation and has been dismantled in 2008 and 2009. The sample specimens have been retrieved and an extensive Post Irradiation Examination (PIE) campaign has started in April 2010 on a selection of materials, under the grant F4E-2009-GRT-030-03.

HIDOBE-02 irradiation

Irradiation of HIDOBE-02 is ongoing and will be completed at the end of May 2011. It has then been irradiated for roughly four years and will have achieved ~90% of its initial target.

HICU

HICU (Acronym for High neutron fluence Irradiation of pebble staCks for fUsion) has the objective to investigate the impact of a fusion reactor neutron spectrum on ceramic breeder pebble beds, as used in a HCPB. The influence of constraining conditions on the thermo-mechanical behaviour on the pebble beds is studied. The irradiation rig features a cadmium shield to tailor the neutron spectrum in order to achieve fusion reactor (DEMO) conditions (relevant dpa/He ratio).

Irradiation of HICU started in 2008 and continued in 2009 and 2010. In 2010 four cycles of irradiation (typically 28 days each) were performed, interrupted by the HFR repair. In the fourth cycle in November 2010, rising temperatures in the central, hottest section of HICU indicate that HICU's cadmium shield had been spent (or was burned up). This means that the desired neutron spectrum cannot be achieved anymore in the centre of the experiment. The experiment was taken out of irradiation and additional calculations on the burn-up of the shield and the irradiation target of the ceramic breeder samples in the experiment have been started.

Isotope Production

2010 was another unusual year for the HFR for Isotope Production. For the first weeks of the year until mid February the HFR continued to work at absolute maximum Medical Isotope production capacity. Isotope production was then stopped for the period of the HFR repair at a time of continuing Medical Isotope shortage and then restarted with a more normal operating pattern in September 2010.

Until the HFR repair Medical Isotope production continued to be given the highest possible priority; with the HFR configuration and operating priorities set to ensure the absolute maximum production levels of key Medical Isotopes and in particular the production of Molybdenum-99 for ^{99m}Tc generators. This configuration allowed as many as 11 ^{99}Mo 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 >50,000 patient scans per day to be performed worldwide; this represents around 60% of total normal world demand. The HFR then stopped isotope production to allow the essential repair work to be carried out. During the repair period, a great deal of effort was given to keeping the Isotope customers and in particular the Nuclear Medicine community informed about the progress of the repair and the projected HFR return to service date. The repair and the communication programme were both successful and NRG received many messages of congratulations about the execution of the work and the open way in which it was communicated to all of the stake holders.

During the supply crisis period of 2009, it was necessary for NRG to reduce the level of production of industrial isotopes and in particular to stop the newly developed Neutron Transmutation Doped (NTP) Silicon business. A process involving the accurate irradiation of Silicon Ingots to produce high quality products used in high voltage and other specialist electronic applications. Following the return to service of the HFR in September 2010, NRG was able to return the HFR to a normal configuration and to resume the production of NTP Silicon.

During that year, NRG continued to work closely with other players in the Medical Isotope supply network, as well as the Medical Community, Governments, the European Commission, the OECD/NEA and the IAEA. These actions were aimed at coordinating efforts to minimizing the effects of the supply problems and to work together towards establishing a future with a greater certainty of security of supply. During 2010 a great deal of process was made, but significant further work is still required in these international forums to establish an enduring long term solution. 2010 once again underlined the critical role performed by the HFR and the supporting NRG infrastructure in the supply of Isotopes for essential medical services.

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Glossary and Acronyms

appm	atomic parts per million
CEA	Commissariat à l'Energie Atomique
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
HB	Horizontal Beam Tube
HELIOS	Helium in Oxide Structure
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)
ISI	In-Service Inspection
ITER	International Thermonuclear Experimental Reactor
JRC	Joint Research Centre
LEU	Low Enriched Uranium
MARIOS	Minor Actinides in Sodium-cooled Fast Reactors
NRG	Nuclear Research and consultancy Group
PIE	Post Irradiation Examination
POSITIFE	Project Pool Side facility Thermally Induced Fatigue
R&D	Research and Development
RAPHAEL	Reactor for Process Heat and Electricity
RTD	Research and Technological Development
SANS	Small Angle Neutron Scattering
TG	Task Group
TN	Technology Network
TYCOMO	TYCO Molybdenum

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Abstract

The High Flux Reactor (HFR) at Petten is managed by the Institute for Energy (IE) of the EC - DG JRC and operated by NRG who are also licence holder and responsible for commercial activities. The HFR operates at 45 MW and is of the tank-in-pool type, light water cooled and moderated. It is one of the most powerful multi-purpose materials testing reactors in the world and one of the world leaders in target irradiation for the production of medical radioisotopes.

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