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Operation and Utilisation of the High Flux Reactor

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HFR operation

Operating schedule

In 2011 the regular cycle pattern consisted of a scheduled number of 293 operation days and two maintenance periods of 19 and 16 days respectively. The In-Service Inspection of the north and south reducer and the annual leak test of the reactor containment were performed during the summer maintenance period in August. In reality the HFR was in operation for 290 days (see Figure 1). This corresponds to an actual availability of 99.22 % with reference to the original scheduled operation plan. Nominal power was 45 MW with a total energy production in 2011 of approximately 13,008 MWd, corresponding to a fuel consumption of about 16.24 kg U-235.The detailed operating characteristics are given in Table 1.

During the reporting period the power distribution measurements for the FLUX 2011 programme and the annual 30 MW reactor training for the operators were carried out. After the scheduled end of each cycle at 45 MW operation, the cycles were directly followed by activities performed in the framework of the regular HFR operators' training.

HFR cycle 11.08 was preceded by short runs of reactivity measurements at low power. The aim of the measurements was to test the reactivity characteristics of two new fresh fuel elements which were fabricated by NCCP. The result of the measurements showed that the characteristics are consistent with regular fuel elements and that the elements could be used as test elements in the HFR starting with cycle 11.08.

All details on power interruptions and power disturbances, which occurred in 2011, are given in Table 2. It shows that twelve automatic reactor scrams, two manual reactor shut-downs and three automatic power decreases occurred (see also figure 2). Two of these scrams were due to human intervention, i.e. human error, and the remaining scrams were due to intervention by the safety systems of the reactor instrumentation devices.

The total discharged activity of tritium and noble gases for 2011 is shown in Figure 3. The licence limit is 100 RE / year. The total discharged activity in 2011 was approximately 12.5 RE.

Maintenance activities

In 2011 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 (0.5 bars overpressure for 48 hours duration) and the In-Service Inspection of the north and south reducers, were also successfully performed. As part of the HFR Modification Plan, several modifications were performed (LOCA 4, 5 and 6). All modifications were implemented after the revision of the plant description and operating instructions and following successful commissioning and testing.

Fuel cycle

Front end

During 2011, 50 Low Enriched Uranium (LEU) fuel elements and 15 control rods (CR) were inspected at the manufacturer's site and delivered to Petten. Since May 2006, the HFR is running completely on LEU fuel.

Back end

In the first quarter of 2011, the last 18 High Enriched Uranium (HEU) spent fuel elements were shipped in a CASTOR MTR2 container to the storage facility (HABOG) of the Dutch Central Organisation for Radioactive Waste (COVRA). After this shipment, all HEU spent fuel elements used in the HFR have been either sent back to the USA (between 2005 and 2006) or stored in the HABOG.

Support has been provided to the "Interfacultair Reactor Instituut" (IRI) of TU Delft in the second quarter of 2011 for transport of spent fuel from the Delft research reactor to the HABOG by making available a MTR-2 container and transport equipment.

In the third quarter of 2011, the "Gesellschaft für Nuklear-Service" (GNS) successfully carried out the compulsory 3 years inspection of the MTR2 container GP-24, the 6 year inspection of the MTR2 container GP-23, as well as of other transport and ancillary equipment.

Table 1: 2011 operational characteristics

			OPERATING TIME					SHUT-DOWN TIME				
Cycle Begin-End	HFR Cycle	Generated Energy	Planned	Low Power	Nom. Power	Other Use	Total	Planned	Unscheduled	Number of Interruptions		Stack Release (of Ar-41)
2011		MWd	hrs	h.min	h.min	h.min	h.min	h.min	h.min	PD	Scram	Bq x E+11
01.01 – 12.01	11.01	510.04	272		272.00		272.05	16.00				2.5
13.01 – 13.02	11.02	1291.83	688	02.05	688.41		690.46	77.08	00.06		1	4.5
14.02 – 16.03	11.03	1247.90	664	03.16	666.09		669.25	74.25	00.10	1	1	4.4
17.03 – 17.04	11.04	1204.75		04.51	640.48		645.39	74.21	47.00		4	4.7
18.04 – 06.05	Maintenance period							456.00				
07.05 – 05.06	11.05	1279.33	688	02.23	681.45		684.08	35.33	00.19		3	3.3
06.06 – 05.07	11.06	1201.73	640	02.34	639.17		641.51	78.00	00.09		2	3.5
06.07 – 07.08	11.07	1281.66	688	05.45	682.16		688.01	102.05	01.54		2	3.8
08.08 – 23.08	Maintenance period and ISI inspection reducers							384.00				
24.08 – 23.09	11.08	1239.51	664	04.20	660.19		664.39	77.39	01.42	1		4.2
24.09 – 24.10	11.09	1253.50	664	02.23	666.45		669.08	74.52				3.5
25.10 – 27.11	11.10	1248.37	688	03.18	661.05		664.23	122.32	30.05	1	1	4.4
28.11 – 28.12	11.11	1232.69	664	01.43	657.45		659.28	84.32				4.7
29.12 – 31.12	12.01	16.94	8	01.55	08.45		10.40	61.20				
TOTAL :		13008.27	7016	35.52	6925.35		6961.27	1717.08	81.25	3	14	43.5
Percentage of total time in 2011 (8760 h):				0.41	79.06		79.47	19.60	0.93			
Percentage of planned operating time (7016 h):				0.51	98.71		99.22					
PD: Power decrease												

Table 2: Full power interruptions of the HFR in 2011

DATE 2011	CYCLE	TIME OF ACTION hour	RESTART OR POWER IN-CREASE hour	NOMINAL/ ORIGINAL POWER hour	ELAPSED TIME TO RESTART OR POWER INCREASE h.min	ELAPSED TIME TO NOMINAL/ ORIGINAL POWER h.min	DISTURBANCE CODE 1	DISTURBANCE CODE MW	DISTURBANCE CODE 2	DISTURBANCE CODE 3	REACTOR SYSTEM OR EXPERIMENT CODE	COMMENTS
11 Feb	11.02	16.16	16.22	16.35	00.06	00.13	AS	0	A	E	Main Power interruption	Main power interruption caused an automatic reactor shutdown.
24 Feb	11.03	16.16	16.22	16.35	00.06	00.13	AP	37.5	R	H	Power demand	By mistake the wrong switch was activated so that the reactor power demand was not switched on, with as result an automatic power decrease.
27 Feb	11.03	00.33	00.43	01.06	00.10	00.23	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
29 Mar	11.04	09.42	08.21	09.30	46.31	47.48	MS	0	R	M	Power demand	The control rod could not be moved due to a defect power demand, the reactor was stopped manually.
01 Apr	11.04	00.42	00.51	01.24	00.09	00.33	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too high with an automatic reactor shut-down as result.
01 Apr	11.04	01.33	01.38	01.55	00.06	00.16	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
14 Apr	11.04	16.04	16.10	16.24	00.06	00.20	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
09 May	11.05	22.33	22.38	23.00	00.05	00.22	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
20 May	11.05	11.00	11.08	11.24	00.08	00.16	MS	0	P	I	Experiment 354-01	Manual shut-down for testing the reactor interlock settings of cooling water systems of experiment 354-01.
31 May	11.05	22.33	22.39	22.50	00.06	00.11	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
14 Jun	11.06	09.21	09.26	09.43	00.05	00.22	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
14 Jun	11.06	11.44	11.48	12.05	00.04	00.21	AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.

DATE 2011	CYCLE	TIME OF ACTION hour	RESTART OR POWER IN-CREASE hour	NOMINAL/ ORIGINAL POWER hour	ELAPSED TIME TO RESTART OR POWER INCREASE h.min	ELAPSED TIME TO NOMINAL/ ORIGINAL POWER h.min	DISTURBANCE CODE 1	DISTURBANCE CODE MW	DISTURBANCE CODE 2	DISTURBANCE CODE 3	REACTOR SYSTEM OR EXPERIMENT CODE	COMMENTS
01 Aug	11.07	14.18	14.22	14.39	00.04	00.21	AS	0	P	I	Experiment 292-01	Cooling water pressure of experiment 292-01 too high with an automatic reactor shut-down as result.
07 Aug	11.07	06.10					AS	0	P	I	Experiment 354-01	Cooling water pressure of experiment 354-01 too low with an automatic reactor shut-down as result.
02 Sep	11.08	11.40	11.44	11.48	00.04	00.08	MP	35	P	S	Experiment 354-02	Reactor power temporary decreased to 35 MW to check if the production of bubbles in the cooling water outlet of Prod. Facility 354-02 depends on the reactor power.
29 Oct	11.10	22.29					AP	0	R	A	Reactor Ventilation	Reactor ventilation stopped due to the failure of a relay in the instrumentation. This caused an APD to 0 MW
31 Oct	11.10		03.45	04.15	30.01	00.30					Restart	After repair and Xenon decay the reactor was restarted on 31 Oct at 03.45 hr.
04 Nov	11.10	08.34	08.38	09.03	00.04	00.25	AS	0	A	E	Main power interruption	Main power interruption caused an automatic reactor shutdown

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	

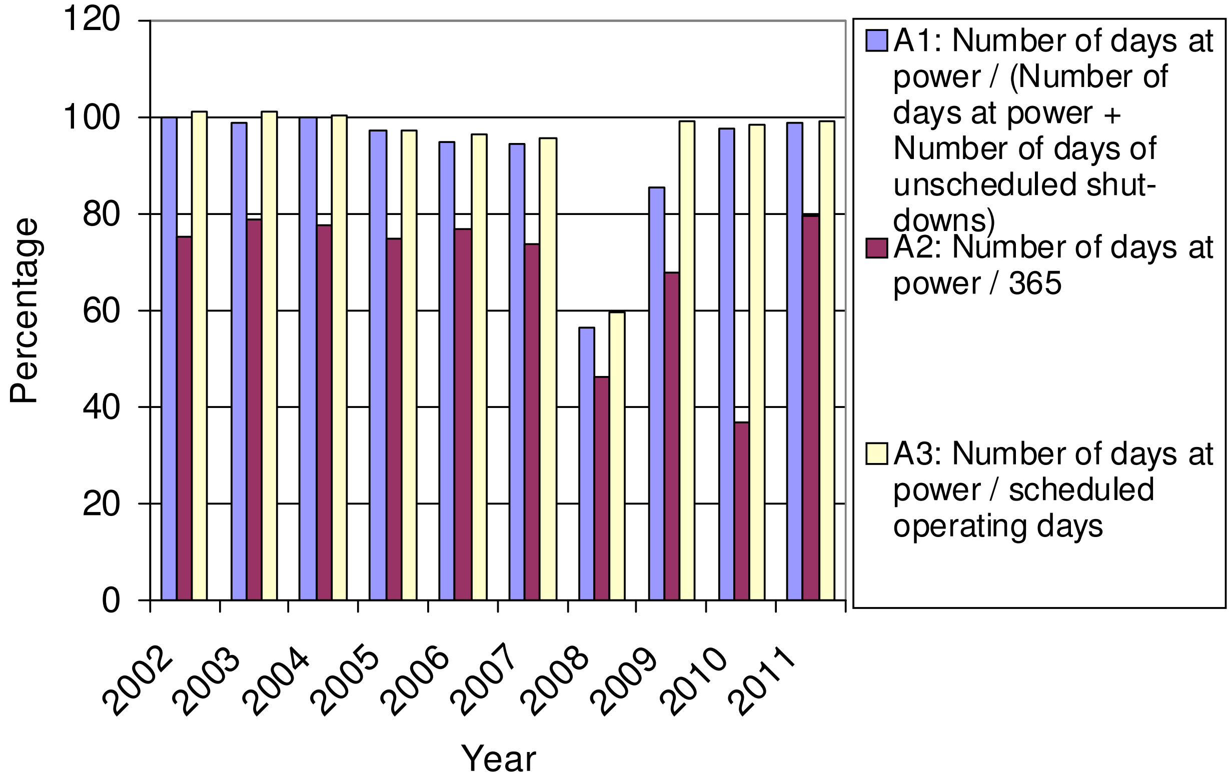

Figure 1: HFR availability

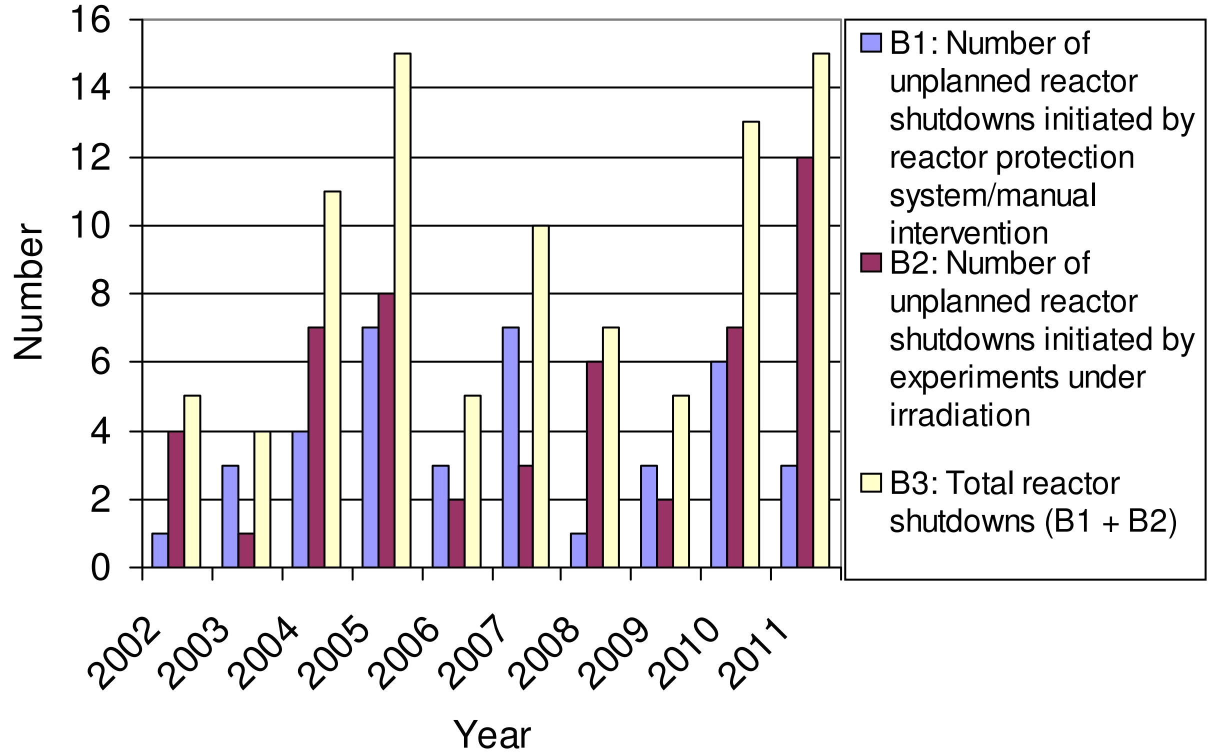

Figure 2: HFR unscheduled shutdowns

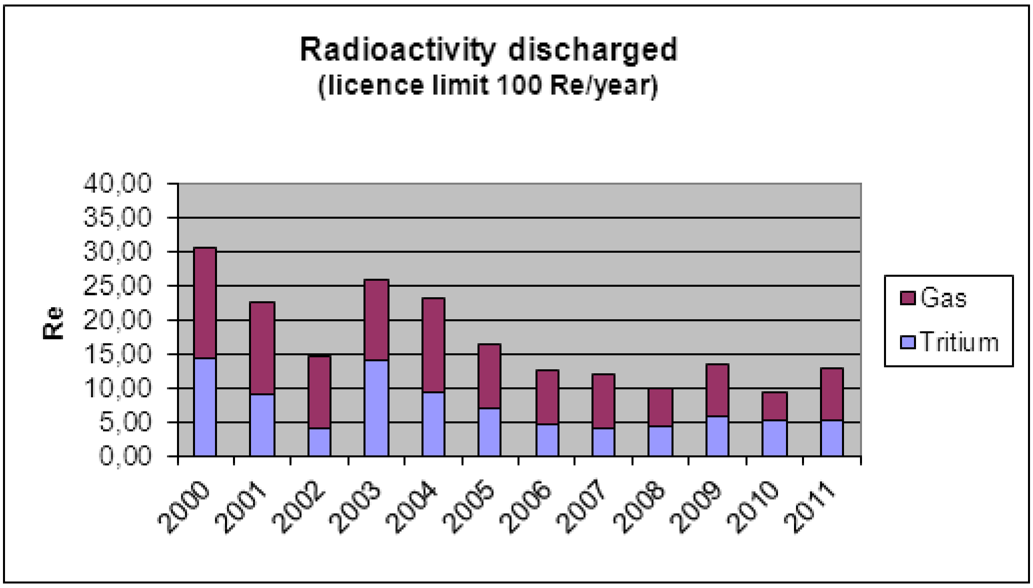

Figure 3: Radioactivity discharge for 2000-11

INSARR 2011

At the request of the Dutch authorities, a full scope IAEA-INSARR mission (INtegrated Safety Assessment of Research Reactors) investigated the HFR in March 2011. The general objectives of the mission were to conduct a comprehensive safety review of the HFR research reactor according to the applicable documents and standards of IAEA.

The findings/recommendations formulated in the previous IAEA INSARR mission (13-18 February 2005) and in the 2010 IAEA inspection dedicated to the repair of the Bottom Plug Liner (BPL) were also scrutinized, in order to determine the degree of implementation of the related corrective actions. The safety areas to be examined in detail were determined in a Pre-INSARR mission in January 2011.

The INSARR Team (3 IAEA experts + 5 external experts) and inspectors of the Dutch regulatory body conducted the review by means of documentation analyses, facilities walk-through, observation of the operations and interviews with the personnel.

The INSARR review concluded that all the recommendations/suggestions deriving from the safety review regarding the BPL repair and about 50% of those deriving from the INSARR 2005 have been addressed. The implementation of the corrective actions will be completed in 2012.

HFR as a Tool for Research

Network on Neutron Techniques Standardization for Structural Integrity (NeT)

The European Network on Neutron Techniques Standardization for Structural Integrity (NeT) supports progress towards improved performance and safety of European nuclear energy production systems. The JRC organises and manages the Network and it 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 2011, the 19th and 20th Steering Committee Meetings of NeT took place in June and December, respectively. About 35 organisations are actively participating in the work of NeT, including eight organisations from the new EU member states and three organisations from candidate countries. From outside the EU, organisations from Japan, Australia and Russia are actively contributing to NeT. Furthermore, in 2011 for the first time measurements for NeT have been undertaken at the Spallation Neutron Source in Oak Ridge, TN, USA.

While the final output documents of the first Task Group of NeT are being drafted, a new activity has been defined on residual stress investigations in a welded nickel-base alloy plate. Other possible future activities have been under discussion during the year. NeT Task Group 1 has been setting a benchmark for numerical and experimental work available to nuclear engineers throughout the world for testing, in particular, the performance of their numerical methods.

Neutron Diffraction Investigations at the HFR

In the reporting period a feasibility study has been undertaken for diffraction measurements in the nickel-base alloy that is considered for the next Task Group within NeT. Nickel has a considerably higher neutron attenuation coefficient than iron, and in addition it also produces a stronger background signal in neutron scattering. These effects result in higher limitations in the material thickness that can be covered by neutron diffraction experiments and in the need for longer counting times at comparable peak intensity due to the higher background. It was therefore necessary to obtain a quantitative estimation of the magnitude of the problems in order to define the geometry of the specimens to be investigated.

The measurements were undertaken at the Large Component Neutron Diffraction Facility at beam tube HB4 at the HFR. They resulted in an estimate for the attenuation coefficient of 0.175 mm^{-1}, relevant to the particular nickel-based alloy and relevant to the (111)-crystallographic reflection plane. As expected, this is considerably higher than the corresponding values observed for iron-based alloys in the past. Based on the findings it was concluded that specimens with a thickness of 12 mm could be investigated. Consequently it was decided at the NeT Steering Committee Meeting in December 2011 that specimens of this thickness would be manufactured for the new Task Group.

Fuel irradiations

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-IET work closely together on the HFR irradiations that are scheduled in FAIRFUELS.

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). 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 a uranium oxide matrix carrier. In these targets, large amounts of helium are produced, which causes significant damage to the material under irradiation. It is the first time that 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.

Achievements
After having obtained the approval for the irradiation, the MARIOS irradiation started as planned on 19 March 2011. The aim of MARIOS, in terms of controlled working temperature of the fuel pellets, are very strict and the first cycle showed a small deviation from that expected. Nevertheless, due to the large operational margins foreseen in the design of the experiment, it was possible to successfully correct the deviation already from the second cycle. MARIOS will run till 1st April 2012 (approximately 300 days).

SPHERE

Objective:
Within the FP7 FAIRFUELS project, the irradiation test SPHERE has been planned for 2012. 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 is 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 2012 and will last for approximately 300 full power days.
The preliminary design for the SPHERE irradiation test has started and also the first fabrication trials at JRC-ITU have been started.

Achievements
During 2011, the preliminary design of SPHERE has been finalised. The fuel has been fabricated at JRC-ITU and some preliminary nuclear analyses have been concluded.

Materials Irradiations

BLACKSTONE irradiations

The UK has a fleet of Advanced Gas Cooled Reactors (AGRs) operated by EDF 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 subjected to accelerated degradation in the HFR. The results are designed to enable the future condition of the AGR graphite to be predicted with confidence.

The first 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 larger part of the post-irradiation examinations have been performed in 2011. In the meantime two new irradiations have been designed and built to achieve higher dose and weight loss and to irradiate material from different AGRs. The objective of these experiments is to consolidate the database produced in phase I and to provide an extensive properties database for graphite from the Hartlepool / Heysham 1 (HRA/HYA) AGRs. These Phase II experiments were loaded into the HFR core in August 2011 and will be irradiated for a total of 11 and 16 cycles respectively.

LYRA-10

The LYRA irradiation rig is used in the framework of the AMES (Ageing Materials and Evaluation Studies) European Network activities with the main goal of studying the irradiation behaviour of reactor pressure vessel (RPV) steels, thermal annealing efficiency and sensibility to re-irradiation damage.

The LYRA-10 experiment housed in the Pool Side Facility (PSF) of the High Flux Reactor (HFR) consists in the irradiation of different specimens representative of reactor pressure vessel materials, namely model steels, realistic welds and high-nickel welds. The model steels comprise of 12 batches of steels with the basic, typical composition of WWER-1000 and PWR reactor pressure vessel materials used by the JRC-IET with the scope of understanding the role and influence of Ni, Si, Cr and Mn as alloying elements and certain impurities as C and V on the mechanical properties of steels.

The realistic welds are created at eight different heats, specially manufactured on the bases of typical WWER-1000 weld composition with variation of certain elements, such as Ni, Si, Cr and Mn. They are of importance to investigate the role and synergisms of alloying elements in the radiation-induced degradation of RPV welds.

The LYRA-10 irradiation campaign started in May 2007 and up to now underwent six HFR cycles at an average temperature of 283 °C with an accumulated fluence in the samples of ~34 x 10^{22} n m^{-2} (E>1 MeV). Originally planned to be irradiated for 7 more cycles to achieve a fast fluence of ca. 6 x 10^{23} n m^{-2} (E>1 MeV), it has been decided during the LYRA-10 outage that at least 10 more cycles will be required to allow the analysis of an hypothetically late-blooming effect that may take place in the irradiated materials.

In order to proceed to the resumption of the LYRA-10 experiment, some mechanical testing and other revamping actions have taken place in 2011. Hence, the LYRA-10 feeding lines, which form part of the gas panels to the connection set next to the pool) were adapted following the change in the HFR glove box system. The experiment connection head was completely renewed (i.e. removal of the plastic hose, gas lines, etc.) and commissioned. Most of the still-pending technical issues were resolved in 2011, LYRA-10 is expected to be irradiated again in the PSF in 2012.

Irradiations for Fusion Technology

CORONIS

Objectives and background
In 2011 a new project started in the area for material development and characterisation for ITER. This project is conducted in the framework of Fusion for Energy, the Europe Joint Undertaking for fusion energy, founded in 2007.

The objective is to measure the tensile, fatigue and Charpy impact properties of CuCrZr material and CuCrZr/316L joints before and after irradiation to 0.01, 0.1 and 0.7 dpa at 250 ºC. This material is foreseen in the shielding blanket in ITER due to the high heat dissipation of CuCrZr to the ITER cooling water. This property can be jeopardised if the material would fail during its operational lifetime in ITER.

The irradiation will be performed with the Hungarian Institute AEKI, who will take account of the low level dose irradiation (0.01 dpa). All post-irradiation experiments will be performed at the NRG Hot Cells. The project will run from January 2011 to September 2013. The project is financed by the Dutch Ministry of Economic Affairs and Fusion for Energy

Achievements in 2011
The irradiation design of the two capsules to be irradiated in the HFR was completed during 2011 including the Design and Safety licence trajectory. The capsule consists of an assembly of tensile and Charpy specimens and will be filled with sodium to increase the heat transfer during irradiation. The capsules, named CORONIS 01 and CORONIS 2 will be irradiated in positions H2 and G3 in the HFR for 1 and 3 cycles respectively. The start of irradiation is planned for cycle 12-06.

Isotope Production

After three disrupted operational years for isotope production in the HFR, 2011 was a year with a normal operational pattern as experienced in the years before 2008. Once again, the HFR was able to demonstrate that it plays an essential role as the largest producer of medical isotopes in Europe and one of the largest producers in the world. The total volume and value of the isotopes and associated services supplied from the HFR grew again in 2011.

New interesting product development ideas progressed, both in conventional application areas, as well as some ground breaking areas of medical technology. Existing development projects also progressed well.

The production of Neutron Transmutation Doped (NTD) silicon for the specialist electronics industry was resumed after the final repair of the HFR in September 2010. During 2011, NRG returned to using a standard configuration of the HFR production facilities and reintroduced the irradiation of silicon ingots to produce high quality products used in high voltage and other specialist electronic applications that can only be served with NTD silicon.

In 2011 NRG continued to work closely with other players in the Medical Isotope supply network, as well as with the Medical Community, Governments, the European Commission, AIPES, the OECD/NEA and the IAEA. These actions were to continue to support the coordinated efforts necessary to minimise the future risks to security of supply of critical medical isotopes.

The HFR fully supports the recommendations of the NEA/OECD High Level Group on the security of supply of medical isotopes. NRG is working together with other international stakeholders on important issues such as full-cost recovery, outage reserved capacity provision, future infrastructure investment and conversion to LEU targets for Mo-99 production. Further work to ensure the sustainable supply of medical isotopes will be carried out in these international forums to establish an enduring long term solution.

Glossary and Acronyms

DG	Directorate General
dpa	displacements per atom
EC	European Commission
EU	European Union
FAIRFUELS	Fabrication, Irradiation and Reprocessing of FUELS and target for transmutation
FLUX	Fluence Rate
FP or FWP	Framework programme
HB	Horizontal Beam Tube
HEU	High Enriched Uranium
HFR	High Flux Reactor
HRA/HYA	Hartlepool /Heysham 1 (AGR) Plants
IAEA	International Atomic Energy Agency
IET	JRC Institute for Energy and Transport, Petten (NL)
INSARR	INtegrated Safety Assessment of Research Reactors
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

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Abstract
The High Flux Reactor (HFR) at Petten is managed by the Institute for Energy and Transport (IET) 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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