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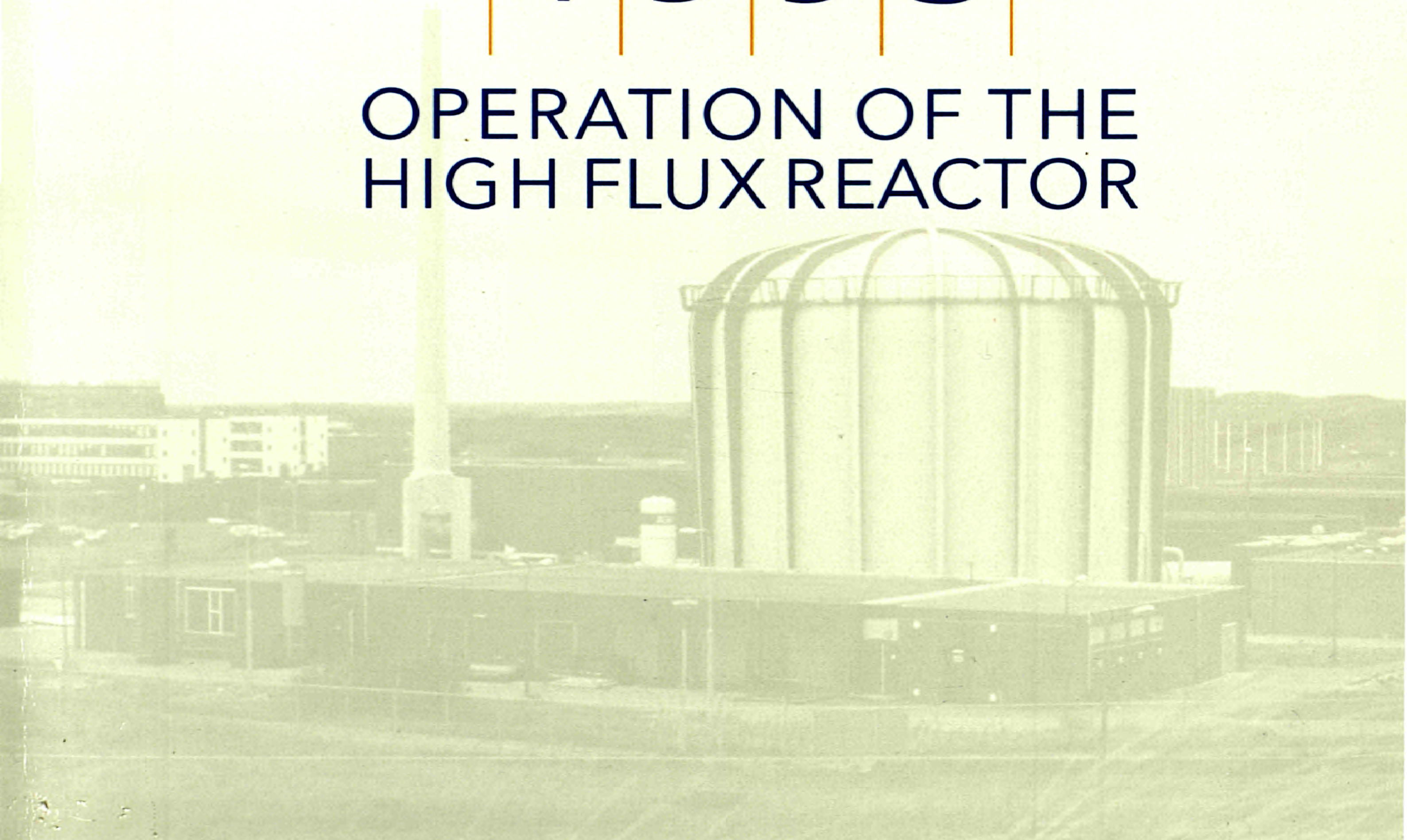
# ANNUAL REPORT 1993

## OPERATION OF THE HIGH FLUX REACTOR



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# ANNUAL REPORT
# 1993
# OPERATION OF THE HIGH FLUX REACTOR

J. Ahlf, A. Gevers,
editors

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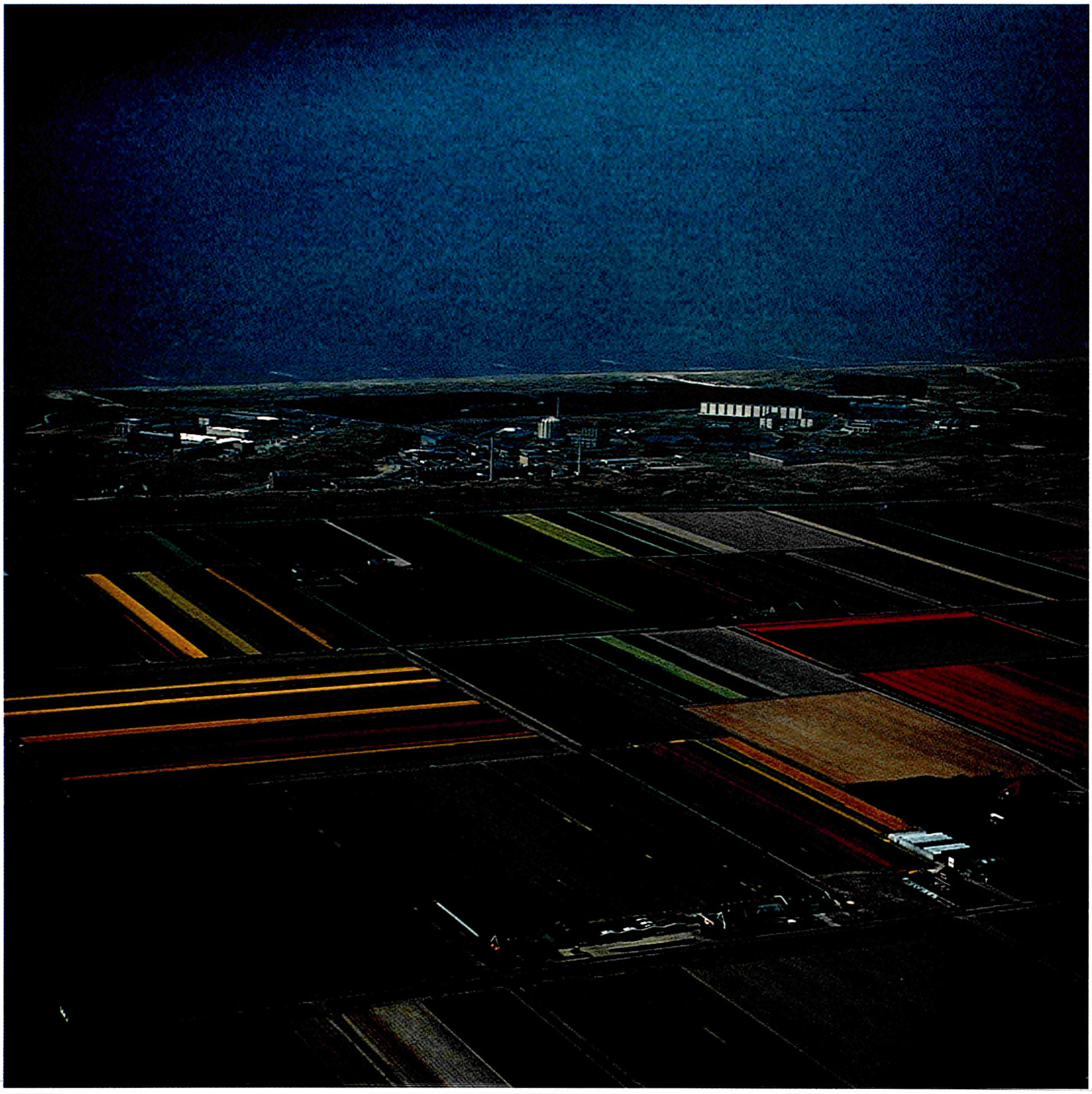


Tulip fields with the High Flux Reactor and Petten research laboratories in the background

# 1. INTRODUCTION

The High Flux Reactor (HFR) Petten belonging to the Institute for Advanced Materials of the Joint Research Centre of the European Communities, is one of the few high power multi-purpose materials testing reactors still in operation in Europe.

The HFR is of the tank-in-pool type, it is light-water cooled and moderated, and it is operated at 45 MW at a prescribed schedule of 11 cycles per year, each comprising 25 operation days and 3 shut-down days. The reactor provides of a variety of irradiation possibilities in the reactor core, the reflector region as well as outside the reactor vessel in so-called poolside facilities. Twelve horizontal beam tubes are serving a neutron scattering laboratory and a number of other purposes.

In 1993 a total of 279 operation days were achieved , corresponding to an overall availability of 76%. The HFR demonstrated again its high reliability with not more than 8 unscheduled interruptions of regular operation. Occupational dose was kept at a low level again, and there were no safety related incidents. Apart from a considerable number of regular maintenance activities, the following upgrading and modification projects are noteworthy:

- full renovation of the secondary cooling water outlet line which had degraded due to 30 years of sea water action,
- renewal of the chlorine injection system of the secondary cooling piping as required by the authorities,
- renewal of the HFR mains power distribution cabinet.

As a matter of high priority, further significant efforts were made with regard to quality assurance towards safe and efficient operation of the reactor which in itself is an explicit programme objective.

In the year 1993, the HFR has continued to serve a remarkably broad users community. The exploitation programme encompassed fission reactor technology with fuel and structural materials investigations, the technology of materials for thermonuclear fusion with damage studies on all kinds of structural materials as well as performance testing of blanket breeder materials, it also encompassed – though at a reduced level – fundamental research with neutrons, and, as a steeply increasing activity, large scale radioisotope production mainly for medical applications; neutron activation analysis, neutron radiography and other irradiation services were offered as well; lastly, research towards cancer therapy with neutrons, known as Boron Neutron Capture Therapy or BNCT, was successfully continued. The irradiation capacity of the HFR was used at a rate of 60% (63% in 1992).

The sectorial breakdown of the HFR utilization shows a further remarkable decrease of nuclear energy related programmes, whereas radioisotope production, mainly for the medical sector, has experienced another significant increase, a fact which clearly demonstrates that high power research reactors are of paramount importance for supporting nuclear medicine.

The following highlights of the ongoing irradiation projects are noted:

- Power ramping and power cycling tests with pre-irradiated LWR fuel rods, $UO_2$ as well as $(U,Pu)O_2$ fuel are now concentrating on high burn-up PWR fuel rods.
- A full size proof test of spherical HTR fuel elements was successfully terminated after an operation time of 634 full power days at operation conditions characteristic for an HTR-MODUL.
- For the EFR project, four irradiation experiments were completed, involving the irradiation of 7 fuel pins, and with irradiation programmes that included 3, successfully performed, dedicated transients to high, overpower conditions. For the advanced (FBR) fuels programme of the ITE at Karlsruhe, another experiment on mixed nitride fuel was completed and an experiment, using mixed oxide fuel was started. The latter fuel pin included 3 specially manufactured fuel pellets containing different quantities of technetium, as part of a pathfinding study into the transmutation fission products.
- The first one years cycle of a long-term irradiation experiment on Zircalloy creep and growth specimens was successfully completed including specimen recovery and measurement in the hot cell and their re-encapsulation into a sodium-filled capsule in the purposely upgraded EUROS cell.
- In a long-lasting irradiation campaign on boron carbide the irradiation temperature could be kept in the required narrow range despite largely decreasing heat production due to burn-up of the boron.
- Structural materials for fusion applications, mainly different kinds of steels, were irradiated at large scale at different temperature levels; considerable effort was required to adapt the irradiation capsules to new specimen sizes and shapes.
- For JET, different components like epoxy resins, insulation materials, cameras, cables, motors, lenses, etc. were irradiated in neutron and gamma fields specially tailored to the actual operating conditions at JET.
- Radioisotope production increased considerably; the HFR is now serving all main European radio-chemical and radio-pharmaceutical companies and is the largest radioisotope producer in Europe; significant effort was required to further upgrade the set of dedicated irradiation devices, in particular for the irradiation of fissile targets for $^{99}$Mo production.
- Within the BNCT project, the healthy tissue tolerance study on a large animal model was successfully completed; significant progress was made with the set-up of a clinical facility for human patients.

Lastly it is noted that a new edition of the users guide, "High Flux Reactor (HFR) Petten – Characteristics of the Installation and the Irradiation Facilities", EUR 15151, has been published. This report provides a comprehensive guidance for all potential users of the neutron services offered at the HFR.

# 2. HFR OPERATION, MAINTENANCE, DEVELOPMENT AND SUPPORT

## 2.1. OPERATION

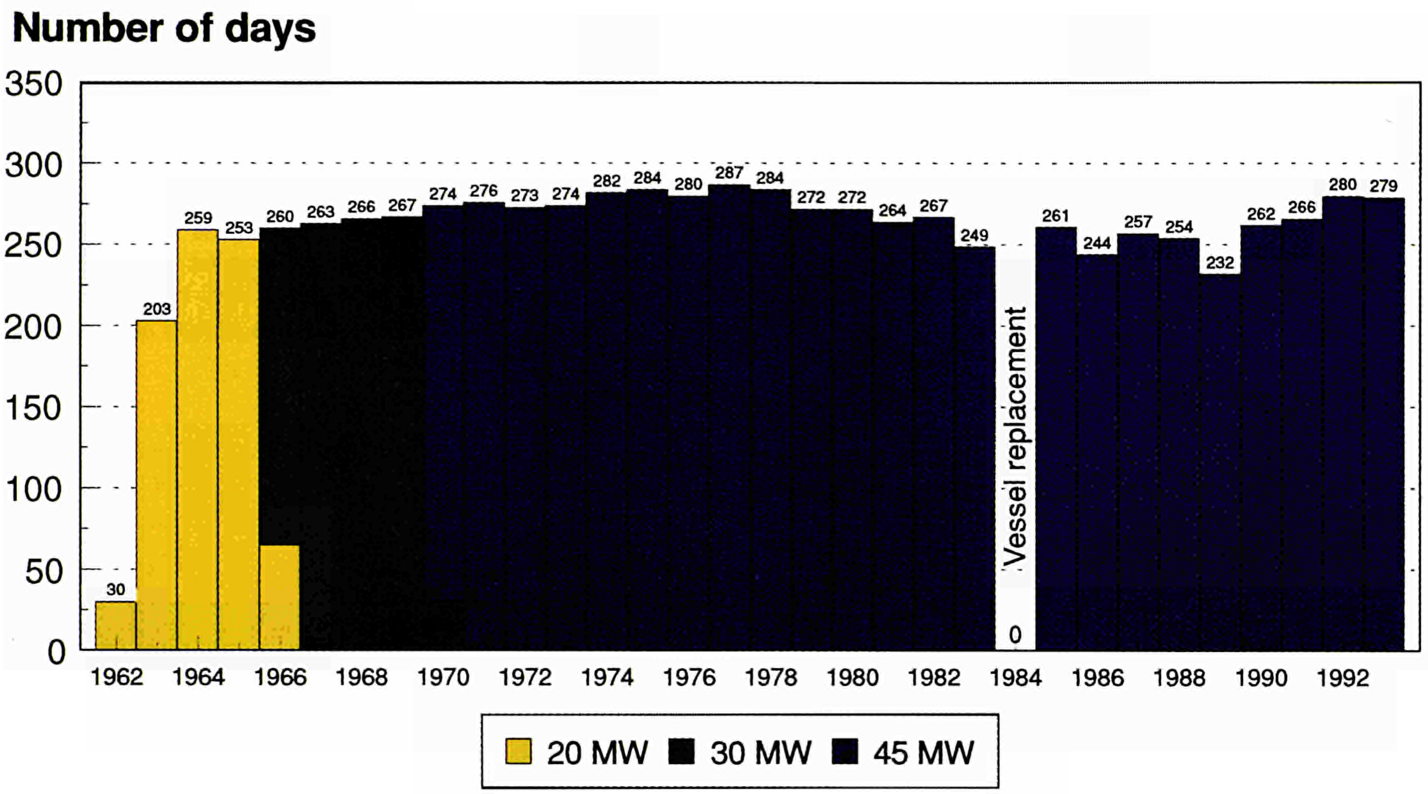
In 1993 the regular cycle pattern, as planned, consisted of a scheduled number of 273 operation days, and two maintenance periods of 30 and 28 days. In reality the HFR has been in operation during 279 days **(fig. 1)**, closely following the scheduled operation plan, which corresponds to an overall availability of 76%. Nominal operation power has been 45 MW. Total energy production has been approximately 12495 MWd, corresponding to a fuel consumption of approximately 15.6 kg U-235.

At the beginning of the reporting period, the HFR was in operation for the completion of cycle 92.11 up to 11 January 1993. Since then the HFR was operated for 9 complete cycles. In order to provide for isotope production during the summer period, HFR cycle 93.07 was performed in two parts to fill a gap in European supply. At the end of the reporting period cycle 93.11 was still in progress, scheduled for completion at January 10, 1994. The operating characteristics for this period are given in **table 1**.

**Table 1**
Operational characteristics

| Cycle begin-end 1993 | HFR cycle | Generated energy MWd | Operating time | | | | | Shut-down time | | Number of interrupt-ions | Stack release (for Ar-41) GBq |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Planned hour | Low power h.min | Nominal power h.min | Other use h.min | Total h.min | Planned h.min | Un-scheduled h.min | | |
| 01.01-11.01 | 92.11 | 428.56 | 256 | 01.39 | 227.43 | | 229.22 | | 34.38 | 1 | 246 |
| 12.01-08.02 | 93.01 | 1136.32 | 592 | 02.05 | 604.55 | | 607.00 | 64.55 | 00.05 | 1 | 1091 |
| 09.02-08.03 | 93.02 | 1133.75 | 592 | 05.24 | 601.31 | 01.05 | 608.00 | 64.00 | | | 512 |
| 09.03-04.04 | Maintenance period | | | | | | | 647.00 | | | |
| 05.04 | Flux 93 | 0.40 | | 00.14 | | 01.00 | 01.14 | 22.46 | | | |
| 06.04-07.04 | Maintenance period | | | | | | | 48.00 | | | |
| 08.04-03.05 | 93.03 | 1116.61 | 592 | 02.13 | 594.32 | | 596.45 | 27.10 | 00.05 | 1 | 536 |
| 04.05-31.05 | 93.04 | 1170.48 | 592 | 03.29 | 622.39 | | 626.08 | 45.46 | 00.06 | 1 | 593 |
| 01.06-28.06 | 93.05 | 1133.98 | 592 | 01.28 | 603.29 | | 604.57 | 67.03 | 650 | | |
| 29.06-26.07 | 93.06 | 1127.39 | 592 | 02.03 | 604.25 | | 606.28 | 65.32 | 796 | | |
| 27.07-11.08 | 93.07.01 | 603.83 | 312 | 01.51 | 321.34 | | 323.25 | 60.25 | 00.10 | 2 | 362 |
| 12.08-08.09 | Maintenance period | | | | | | | | | | |
| 08.09 | | 11.59 | | | | 27.26 | 27.26 | 644.34 | | | |
| 09.09-20.09 | 93.07.02 | 501.47 | 280 | 02.34 | 265.23 | | 267.57 | 20.03 | | | 260 |
| 21.09-18.10 | 93.08 | 1121.44 | 592 | 01.32 | 592.30 | 16.02 | 610.04 | 62.56 | | | 570 |
| 19.10-15.11 | 93.09 | 1158.68 | 592 | 10.18 | 588.15 | | 598.33 | 73.27 | | | 591 |
| 16.11-13.12 | 93.10 | 1147.12 | 592 | 01.18 | 610.40 | | 611.58 | 59.58 | 00.04 | 2 | 720 |
| 14.12-31.12 | 93.11 | 702.83 | 360 | 01.07 | 373.30 | | 374.37 | 57.23 | | | |
| Total | | 12494.45 | 6536 | 37.15 | 6611.06 | 45.33 | 6693.54 | 2030.58 | 35.08 | 8 | 7200 |
| Percentage of total time in 1993 (8760 h) | | | | 0.4% | 75.5% | 0.5% | 76.4% | 23.2% | 0.4% | | |
| Percentage of planned operating time (6536 h) | | | | 0.6% | 101.1% | | 102.4% | | | | |

**Fig. 1**
HFR operation days, 1962-1993



Special operation runs, mostly at low power, were carried out for neutron spectra measurements in preparation for the Boron Neutron Capture Therapy facility and other irradiation projects and for control rod calibration. Regular reactivity measurements of irradiation experiments have been carried out. An example of a typical core loading with corresponding power pattern and control rod position is shown in **fig. 2.**

Deviations from nominal power level occurred 21 times during 1993, 13 of these were scheduled, mostly for intermediate handling or adjustment of irradiation facilities. The remaining 8 were related to technical failures, human interactions or experiment related events. Detailed characteristics of all power disturbances are given in **table 2.**

**Table 2**
Full power interruptions

| Date | Time of | | | Elapsed time to | | Disturbance code | | | | Reactor system or experiment code | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1992 | Action hour | Restart or power increase hour | Nominal/ Original power hour | Restart or power increase h.min | Nominal/ Original power h.min | 1 | MW | 2 | 3 | | |
| Jan 02 | 17.17 | | | | | AS | 0 | R | I | Interlock | Magnet current |
| Jan 04 | 03.55 | 05.15 | 34.38 | 35.58 | | | | | | | |
| Jan 06 | 00.15 | 00.19 | 00.21 | 00.04 | 00.06 | MP | 35 | E | S | 136 | Facility handling |
| Jan 06 | 00.52 | 01.01 | 01.05 | 00.09 | 00.13 | MP | 35 | E | S | 136 | Facility handling |
| Febr 01 | 14.18 | 14.24 | 14.26 | 00.06 | 00.08 | MP | 35 | E | S | 136 | Facility handling |
| Febr 03 | 03.40 | 03.45 | 04.01 | 00.05 | 00.21 | AS | 0 | E | I | BWFC-A | Electrical fuse |
| Febr 08 | 00.06 | 00.10 | 00.12 | 00.04 | 00.06 | MP | 35 | E | S | 136 | Facility handling |
| Febr 17 | 00.04 | 00.09 | 00.14 | 00.05 | 00.10 | MP | 35 | E | S | 136 | Facility handling |
| Febr 17 | 00.44 | 00.49 | 00.56 | 00.05 | 00.12 | MP | 35 | E | S | 136 | Facility handling |
| Febr 24 | 00.09 | 00.22 | 00.29 | 00.13 | 00.20 | MP | 35 | E | S | 136 | Facility handling |
| Febr 24 | 01.26 | 01.47 | 01.56 | 00.21 | 00.30 | MP | 25 | E | S | 215 | Experiment handling |
| Febr 24 | 10.39 | 10.52 | 11.02 | 00.13 | 00.23 | MP | 25 | E | S | 215 | Experiment handling |
| Febr 24 | 18.34 | 18.40 | 18.43 | 00.06 | 00.09 | MP | 25 | E | S | 215 | Experiment handling |
| Apr 28 | 09.51 | 09.56 | 10.10 | 00.05 | 00.19 | AS | 0 | E | H | 215 | Inadvertent power interruptions of a MV-unit |
| May 07 | 14.39 | 14.45 | 15.14 | 00.06 | 00.35 | AS | 0 | R | E | Mains power | Mains dip |
| May 13 | 21.45 | 21.57 | 22.00 | 00.12 | 00.15 | MP | 25 | E | S | 215 | Experiment handling |
| May 14 | 21.11 | 21.21 | 21.24 | 00.10 | 00.13 | MP | 25 | E | S | 215 | Experiment handling |
| Aug 04 | 13.41 | 13.46 | 14.00 | 00.05 | 00.19 | AS | 0 | E | H | 266 | Wrong temperature adjustment |
| Aug 04 | 14.48 | 14.53 | 15.05 | 00.05 | 00.17 | AS | 0 | E | I | 266 | Exceeded cooling water pressure |
| Nov 23 | 16.46 | 16.52 | 16.54 | 00.06 | 00.08 | MP | 25 | E | S | 183 | Experiment handling |
| Nov 28 | 20.03 | 20.07 | 20.21 | 00.04 | 00.18 | AS | 0 | A | E | Mains power | Mains dip |
| Dec 09 | 18.26 | 18.27 | 18.31 | 00.01 | 00.04 | MP | 26 | R | H | Primary temp. | Preventive power decrease |

1. Leading to

| | |
|---|---|
| - automatic shut-down | AS |
| - manual shut-down | MS |
| - automatic power decrease | AP |
| - manual power decrease | MP |

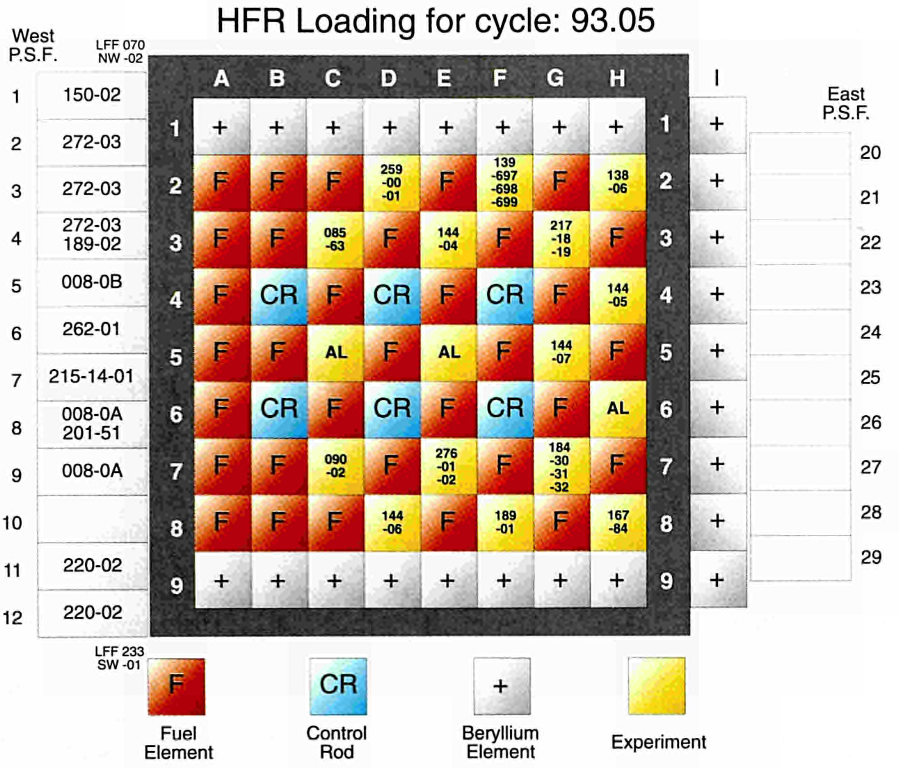
2. Related to

| | |
|---|---|
| - reactor | R |
| - experiment | E |
| - auxiliary system | A |

3. Cause

| | |
|---|---|
| - scheduled | S |
| - requirements | R |
| - instrumentation | I |
| - mechanical | M |
| - electrical | E |
| - human | H |

**Fig. 2**
HFR cycle 93.05. Experiment loading, reactor power pattern and control rod movement



HFR Loading for cycle: 93.05

West P.S.F.

LFF 070 NW -02

| | |
|---|---|
| 1 | 150-02 |
| 2 | 272-03 |
| 3 | 272-03 |
| 4 | 272-03<br>189-02 |
| 5 | 008-0B |
| 6 | 262-01 |
| 7 | 215-14-01 |
| 8 | 008-0A<br>201-51 |
| 9 | 008-0A |
| 10 | |
| 11 | 220-02 |
| 12 | 220-02 |

LFF 233 SW -01

| | A | B | C | D | E | F | G | H | | I |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | + | + | + | + | + | + | + | + | 1 | + |
| 2 | F | F | F | 259<br>-00<br>-01 | F | 139<br>-697<br>-698<br>-699 | F | 138<br>-06 | 2 | + |
| 3 | F | F | 085<br>-63 | F | 144<br>-04 | F | 217<br>-18<br>-19 | F | 3 | + |
| 4 | F | CR | F | CR | F | CR | F | 144<br>-05 | 4 | + |
| 5 | F | F | AL | F | AL | F | 144<br>-07 | F | 5 | + |
| 6 | F | CR | F | CR | F | CR | F | AL | 6 | + |
| 7 | F | F | 090<br>-02 | F | 276<br>-01<br>-02 | F | 184<br>-30<br>-31<br>-32 | F | 7 | + |
| 8 | F | F | F | 144<br>-06 | F | 189<br>-01 | F | 167<br>-84 | 8 | + |
| 9 | + | + | + | + | + | + | + | + | 9 | + |

East P.S.F.

| | |
|---|---|
| 20 | |
| 21 | |
| 22 | |
| 23 | |
| 24 | |
| 25 | |
| 26 | |
| 27 | |
| 28 | |
| 29 | |

| | |
|---|---|
| F | Fuel Element |
| CR | Control Rod |
| + | Beryllium Element |
| 🟨 | Experiment |

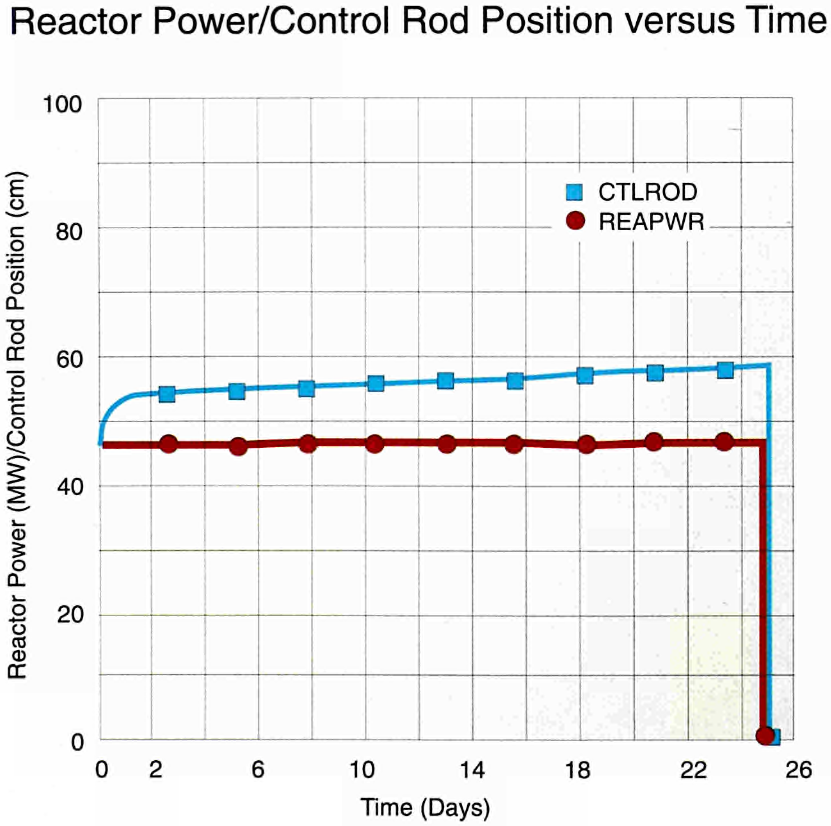
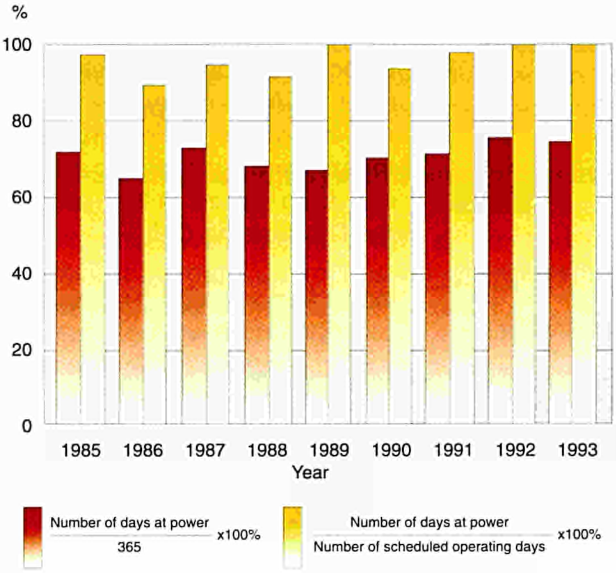


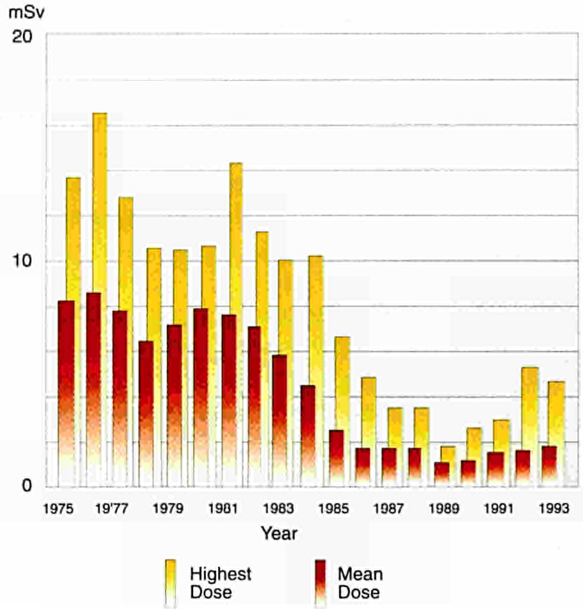
**Fig. 3**
Performance indicators



In **fig. 3** a survey of some commonly used performance indicators from 1985 to 1993 are presented.

A survey of the registered annual radiation doses of HFR operating personnel is given in **fig. 4.** The total collective dose over 1993 for the operating shift personnel is again slightly higher than that of 1992. This is mainly due to again increased isotope handling. The total collective dose over all HFR concerned personnel (maintenance staff included) remained about unchanged.

**Fig. 4**
Dose-equivalent HFR-operators



## 2.2. FUEL CYCLE

During 1993 the ordered new fuel elements and new control rods were delivered on schedule by the manufacturer.

Disposal of spent fuel elements to the reprocessing facility at Savannah River (USA) or elsewhere was still impossible. To provide for room for normal operation an important number of used control rods and fuel elements were cut down to transport lengths
and then stored in the special interim storage facility in the pool below the Dismantling Cell.

## 2.3. TECHNICAL MAINTENANCE

Inspection, overhaul, repair and replacement of the technical systems and components have been carried out mainly during the planned maintenance periods in March and August 1993. A large part of the maintenance personnel attended a course on the QA/QC aspects applied in the nuclear field by an external firm. Some special items concerning technical maintenance are described below.

### 2.3.1. Mechanical Installations

All experiment passages through the top cover of the reactor vessel were checked dimensionally and accepted without further actions needed. Gridbars were inspected visually, all bolt torques were checked. Control rod drive mechanisms of positions B6, D6 and F6 were overhauled.

Extensive acceptance testing has been carried out with an upgraded trolley drive mechanism for the poolside facility installations (a.o. titanium slide bearings). In situ testing is foreseen.

Following periodical maintenance procedures for the primary system one main pump was completely overhauled. NDE checks proved shaft and impeller to be without flaws; bearings and impeller rings were replaced. The N-16 decay tank was drained and inspected internally. The heat exchangers were visually inspected, lengths of the plate packages were checked and found to be within tolerances.

The heat exchanger of the pool cooling system was cleaned, inspected and mounted again. A spare set of titanium heat exchanging plates has been ordered. In the future a complete set of plates can then be exchanged for the spare set, thus facilitating decontamination procedures.

One secondary pump of the secondary cooling system has been completely overhauled. The impeller was balanced at the manufacturers workshop. After assembly the pump was put into operation again. Rotary inlet filter North was cleaned and repainted.

Personnel and vehicle entrances of the containment building were inspected. Packings were renewed and tested for leakages. The partly corroded outside balcony of the building was repaired on several places. Walking grid plates were completely renewed.

Both 20 ton cranes (inside the containment building and in the high construction hall) were tested on their yearly basis by a specialised outside firm. Full certification was continued. Investigation into possibilities to slightly increase the maximum allowable loads in view of expected future handling of slightly heavier fuel flasks has been started.

### 2.3.2. Instrumentation Systems and Informatics

All gasmonitors were provided with easier readable analog meters in the reactor control room on request of operation personnel. A new 4-line recorder was installed for the same reason.

A testing-unit was built to periodically test the multiplexer units of the NEFF dataloggers of the data acquisition system DACOS. Data presentation possibilities were extended with further graphical options: now both linear and logarithmical divisions are available. Special dedicated programmes were written on request for project engineers. An overall maintenance contract for all informatics is being pursued to be available early 1994. A technical specification for a reactor signals datalogger has been drawn up. An additional number of reactor signals will thus also be collected on DACOS, fulfilling both experiment requirements and reactor operational use.

The computer network in the containment building was extended on request of users. Local printing facilities were improved.

### 2.3.3. Electrical Installations

In preparation for and after actual installation of the new main power distribution cabinet a large amount of cables and switch gear had to be rerouted and relocated. Operational procedures, check outs, drawings etc. directly influenced by the replacement were updated before the restart of the reactor. Further technical documentation is being updated.

All signal cables and power supply to the new location of DACOS were rerouted. Additional network cabling in the containment and office buildings was installed.

The control system for the pneumatic rabbit system was redesigned applying a PLC. This system was built, installed and put into operation.

The electrical maintenance personnel was especially instructed by the manufacturer of the main electrical distribution cabinet on the applied techniques and required maintenance methods.

### 2.3.4. Buildings and Site

Paintwork on the outside of the reactor containment building was inspected as required by the guarantee conditions. Local repairs were made. A new layer of paint is to be applied in 1994 to extend the guarantee period. The corroded outside balcony was repaired and partly renewed, all walking grid plates were renewed. The yearly containment building leak-rate measurements, as stipulated by the operation license, were carried out at an overpressure of 0.5 bar. Results were within license conditions.

The floor of the pool cooling compartments of the primary pump building were repaired and re-coated with epoxy resin paint to facilitate decontamination after pool heat exchanger cleaning operations.

Erection of the Non Destructive Examination Laboratory on the reactor complex was finished. The cabling on the HFR complex at the actual building site had to be partly re-routed. Supply of electrical power, telephone, intercom systems, etc. was arranged and connected to existing provisions on the HFR complex.

## 2.4. TECHNICAL AND EXPERIMENTAL SUPPORT

### 2.4.1. Assistance to Experiments

In addition to routine assistance to experiments further assistance was rendered in a substantial way to the work of several project teams, viz. BNCT, Sweeploop and Tritium Measuring Station operation and BWFC.

To further improve ECN Isotope Production Services to clients a newly designed rotating welding machine was introduced to facilitate closure of isotope capsule heads. During welding the capsule contents are kept cool by partly submerging the capsule outside surface in water.

### 2.4.2. Reactor Vessel Material Surveillance (SURP)

Aluminium vessel material samples are being irradiated under different neutron spectrum conditions in order to study irradiation induced changes in the material properties of the HFR vessel. These irradiations were continued in both reactor-core and pool side facility positions during 1993. A study has been carried out to improve the design of the SURP sample holders.

## 2.5. UPGRADING AND MODIFICATION PROJECTS

### 2.5.1. Renovation of the Secondary Cooling Water Outlet

Technical specifications were drawn up by an external specialised firm. The renovation of the secondary cooling water outlet was carried out during the summer maintenance stop under supervision of an outside firm.
The original concrete piping was internally relined with synthetic interconnected pipe sections over the last 195 meters from the outlet. These sections were pushed in from the dune side in seaward direction. For this operation the outlet pipe was cut on purpose at the foot of the dunes and closed afterwards.
The remaining space between the outside of the relining piping and the inside of the original concrete pipe was filled with a special fluid pumped in under pressure thereby replacing the present water. This fluid, a suspension in water with concrete, marl, clay and plaster, starts hardening after 6 to 7 hours. The outlet stop valve was renewed and relocated 75 meters inland to compensate for dune replacement over past years. The

actual outlet diffuser grid was completely renewed.
The breakwater, in which the last part of the piping is situated, was repaired and its top was covered with concrete on request of the authorities. This concrete coverage should also prevent future cracking of the outlet piping **(fig. 5).**

### 2.5.2. Ion Exchanger Drain and Storage System

All tanks and necessary appliances have been delivered. All further assembly work is being carried out by own personnel and is nearing completion steadily.

**Fig. 5**
Preparations for application of concrete coverage of outlet part in breakwater

### 2.5.3. Renewal of the Chlorine Injection System of the Secondary Cooling Piping

Building adaptation for and installation of the new sodium hypochlorite injection system was finished. Operation started with investigation for the optimal sodium hypochlorite dose-rate by closely checking for algae growth at different concentrations. A unit to measure the concentration of free chlorine in the secondary water after passing the heat exchangers, thus halfway the secondary circuit between secondary pumping station and North Sea, has been installed to facilitate this investigation. First impressions look promising.

### 2.5.4. HFR Control Room Upgrading

As part of this project the pneumatic process instrumentation distribution board has been renewed and relocated **(fig. 6)**. The new panel for alarm on the pneumatic signals was approved by the Reactor Safety Committee and KFD.

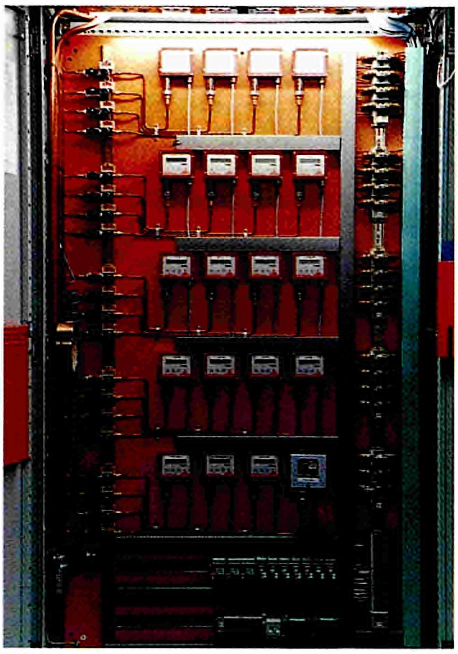


**Fig. 6**
Interior of alarm panel for pneumatic signals

### 2.5.5. Relocation of the DACOS Experiment Data Handling System

During 1993 the building adaptations to relocate the DACOS computer system farther into the "protected zone" and closer to the HFR control

**Fig. 7**
Users room overview

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room were carried out. During these building activities great additional effort was necessary to maintain physical protection measures at all times. Additional safety precautions had to be applied to remove the old asbestos isolated ventilation ducts in a safe manner. The actual relocation of the complete computer system and its peripherals was performed without any negative effect on data collection in the following reactor cycle. Adjacent to the new computer room a dedicated room is now available as a working area for project engineers and HFR experiment operators **(fig. 7)**. In this way traffic in the HFR control room to perform these tasks was reduced considerably. During this project also the entrance doors to the protected zone were replaced by an improved type and the automatic fire alarm system was renewed.

### 2.5.6. Renewal of HFR Mains Power Distribution Cabinet

During the spring maintenance period the old installation, including all peripherals etc., was removed and the new distribution cabinet with integrated "motor control centre" was installed. All main supply – and user cables were renewed. The operation was carried out within the programmed stop period applying a two shift workforce. Electrical supply to essential parts of the installation during the replacement was provided by temporary provisions from the site diesel-driven emergency supply station. A thorough testing and commissioning period preceded reactor restart **(fig. 8)**.

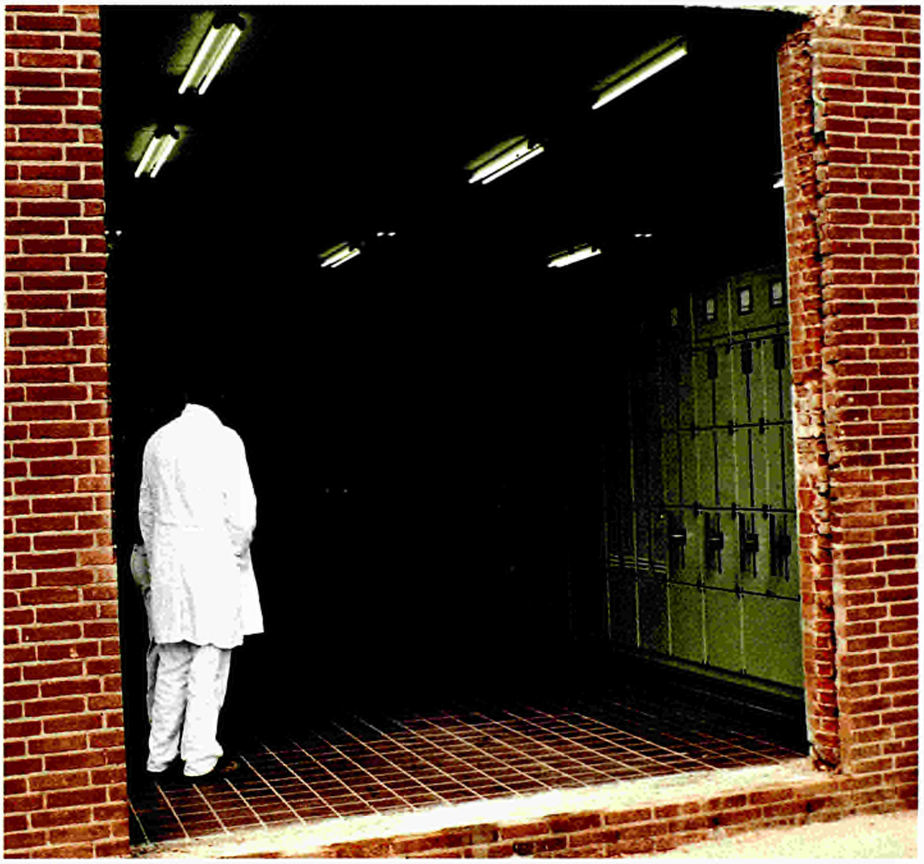


**Fig. 8**
HFR Mains Power Distribution Cabinet.
Final installation

### 2.5.7. Renewal of Original Overpower Protection System

Technical specifications were drawn up for the renewal of the present first set of three safety channels. Ordering and installation is foreseen in 1994.

## 2.6. NUCLEAR SUPPORT

The annual core flux measurements campaign, called FLUX 93, has been carried out in cycle 93.03.

In 1993 the WIMS code suite was introduced at the HFR department. WIMS is a QA code package of Answer Services at Winfrith (UK). Besides diffusion models for core calculations WIMS also possesses transport modules. This enables the HFR department amongst others to perform correct calculations for the PSF environment. Since WIMS will replace in the future the present HFR-TEDDI package, all developments for the latter code are stopped.

In order to reduce the number of fresh fuel elements for a cycle, a study has been performed to analyze the effect on core behaviour. It turned out that loading four fresh fuel elements instead of five, leads to a feasible core with the present experiment loading when fuel elements, which are presently considered as "fully burned up", are added to the operationa stock. The new loading scheme reduces the number of fresh fuel elements for each cycle with one element, which implies a considerable saving in fuel costs.

# 3. HFR UTILIZATION

In 1993 the average utilization rate of the HFR was 60% of the practical occupation limit. The reactor was utilized for research programmes in support of nuclear fission reactors and thermonuclear fusion, for fundamental research with neutrons, for radioisotope production, for BNCT, and for various smaller activities.

## 3.1. LIGHT WATER REACTOR (LWR). FUEL AND STRUCTURAL MATERIAL IRRADIATIONS

Although the technology of light water reactors can be regarded as rather mature, there is still sufficient incentive for research reactor programmes with regard to the optimization of fuel cycle cost, as well as with regard to plant life extension.

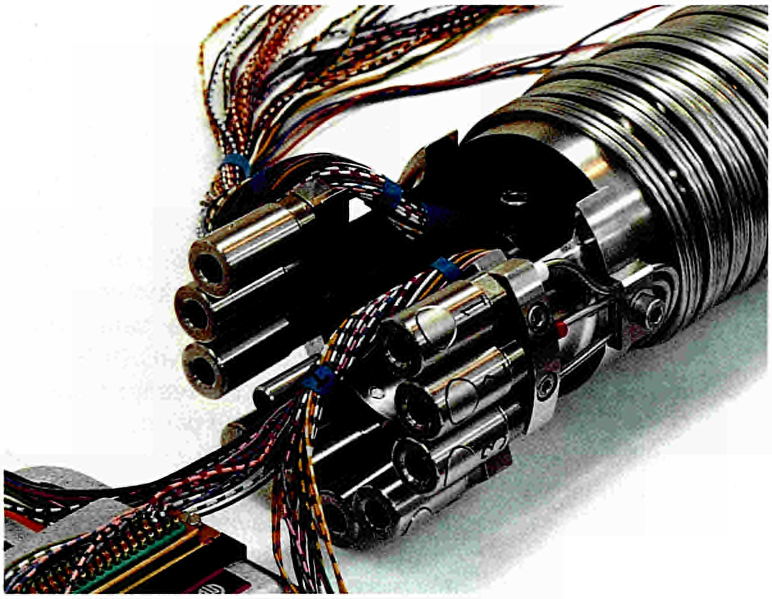


**Fig. 9**
Pre-assembled vertical displacment unit of a standard irradation head

**Fig. 10**
X-ray of an experiment

### 3.1.1. Fuel Rod Irradiation

During the last three decades, the HFR is well known for its irradiation support to LWR fuel research programmes. Important contributions are made in the areas of R&D on fuel and cladding behaviour, the safe and the economic utilization of LWR fuel. The irradiation experiments at the HFR addressed in particular the fuel rod performance and behaviour under start-up, operational and overpower transients and/or under power cycling conditions /1/.

Since 1972, most test programmes are performed with pre-irradiated fuel rod segments which originate from commercial power reactors. Broad experience has been gained at the JRC and the Petten hot cells of ECN in application of this test method /2/. Since 1992, the test capabilities are enlarged with the successful introduction of a re-fabrication technique at the Petten hot cells for test fuel rods made from pre-irradiated full length power reactor fuel rods /6/.

Important data on fuel rod behaviour as a function of burn-up and with respect to its transient behaviour, e.g. safe transient speed, safe power steps and allowable power thresholds have been obtained through these programmes for standard PWR and BWR fuel using $UO_2$ and $(U,Pu)O_2$ [Mixed Oxide Fuel (MOX)] /3/. These data are now being used in operation of to-days power reactors and have led to an increase of availability and economics of the plants.

Recent R&D programmes in the LWR fuel sector are addressing mainly fuel rod behaviour at extended and high burn-up. However, also performance testing of new fuel rod concepts with respect to better waterside corrosion resistance, improved economics (e.g. utilization of MOX) and fine tuning of its characteristics are continued.

A second line of irradiation experiments at the HFR addressed the investigation of the release and behaviour of fission products after a hypothetical LOCA scenario. In particular, the iodine release, its solution and degassing after a LOCA were studied. Major contributions to this topic were achieved in the early 80's through HFR experiments and hot cell tests at KFA Jülich /4/, and in the 90's through an in-pile LOCA testing programme using pre-irradiated PWR fuel rods /8/.

In 1993, the following objectives were addressed by the LWR fuel rod irradiation programmes at the HFR:

- Investigation of power cycling behaviour of extended burn-up PWR fuel rods, and
- Power ramp testing of MOX fuel rods.

In order to qualify the LWR fuel testing facilities and methods following the ISO 9000 quality standards, an action was initiated to convert and update the existent quality systems to these requirements. Until a general ISO 9000 qualification is obtained for the HFR, a project related ISO 9000 qualification system will be employed for new LWR fuel rod testing programmes.

At the ENS TOPNUX '93, the International ENS TOPical Meeting titled "Towards the next generation of light water reactors", held in April '93 at The Hague/Netherlands, an overview about "irradiation technology at the HFR Petten for R&D related to the next generation of LWR's" /7/ was presented. This contribution addresses both, LWR fuel and materials irradiation testing.

Power ramp tests of new or pre-irradiated LWR fuel rods

Within an ongoing irradiation programme which is related to the investigation of high burn-up PWR fuel rods, another power cycling test was performed. The power scenario operated during this test represented 99 day/night power cycles, however, with integral irradiation periods of the various low and high power parts. During the irradiation programme several intermediate inspections for fuel rod characterization took place with non-destructive techniques (e.g. neutron radiography, eddy current measurement of the cladding, profilometry and Kr-85 measurement in the plenum). The experiment was performed with a high burn-up PWR fuel rod (approx. 56 GWd/t(U)) using the "low power" BWFC capsule. All anticipated post irradiation examinations at the Petten hot cells were completed during 1993 on all fuel rods which have been irradiated at the HFR for this programme.

A power ramp testing programme with 3 MOX fuel rods of extended burn-up was successfully performed at the HFR using the existent LWR fuel rod testing facilities. All scheduled post irradiation examinations at the HFR and the Petten hot cells were terminated during the reference period.

Preparations for a new power ramp and power cycling irradiation programme with re-fabricated high burn-up PWR test fuel rods were started. The re-fabrication of the test fuel rods is anticipated for the first half of 1994 at the hot cells of the Joint Research Centre at Karlsruhe. Irradiation testing at the HFR will commence in the second half of 1994.

For another new irradiation programme addressing the irradiation behaviour of pellets with different boron additions to the pellet surface preparative work was undertaken. The irradiation programme will employ dedicated fresh PWR fuel rods with different types of boron additions to the pellet. The start of irradiation testing at the HFR is scheduled for February 1994.

At the Petten hot cells provisions were made for reception of full length LWR fuel rods from nuclear power stations. These provisions are based on the R 52 type transport container and allow direct delivery of irradiated full length LWR fuel rods, or segmented fuel rods of up to 4500 mm length to the Petten hot cells and treatment of the fuel rods for further testing at the HFR. This capability includes the following major steps : Fuel rod reception, puncturing and fission gas analysis, segmentation into segments with a length up to 2000 mm, non-destructive investigations (e.g. gamma scanning, profilometry, eddy current testing), preparation for re-fabrication and re-fabrication of test fuel rods. It is anticipated to employ during 1994 the above facilities within an upcoming BWR fuel rod testing programme using 2 full length LWR fuel rods, each consisting of 7 fuel rod segments. The fuel rods of this test programme have already been tested earlier at the HFR and were returned to the nuclear power plant for additional burn-up accumulation.

### Irradiation testing of PHWR MOX fuel rods

Two irradiation experiments, each using two short fresh MOX PHWR fuel rods, have been performed during 1986 and 1988/91 at the HFR in order to study the fuel rod power ramping behaviour at approx. 15 GWd/t(M) [e.g. end-of-live (EOL) conditions].

During 1993, the irradiation test programme was terminated at Petten and the fuel rods were returned to the clients hot cells for further investigations.

### Irradiation testing of re-fabricated LWR fuel rods

Six test fuel rods have been re-fabricated (during 1991 and 1992) at the Petten hot cells /6/ from fuel rod sections which were taken from two full length fuel rods. The full length fuel rods were previously irradiated for three years in a commercial power reactor.

Irradiation testing of all six fuel rods was performed during 1992 successfully within a preset tight time schedule. The tests consisted of a conditioning and transient irradiation phase. During 1993, the major part of post irradiation activities were completed.

### Iodine Solubility and Degassing Experiment (ISOLDE) with pre-irradiated PWR fuel rods

The test programme addressed the determination of the rate of iodine release from PWR fuel rods and its solution in steam and water for a LOCA scenario starting from PWR conditions.

The last in-pile test in this series /5/ was performed and evaluated during 1992. The test series confirmed earlier findings from the earlier HFR Petten/KFA hot cell programme /4/ using pre-irradiated and at the HFR re-irradiated PWR fuel rods. A summary with the results of the in-pile test programme was presented at the KTG Annual Meeting 1993 at Cologne /8/.

### Development of LWR fuel testing devices

Development activities on existent or for new irradiation devices for LWR fuel irradiations are required to provide up-to-date test techniques.

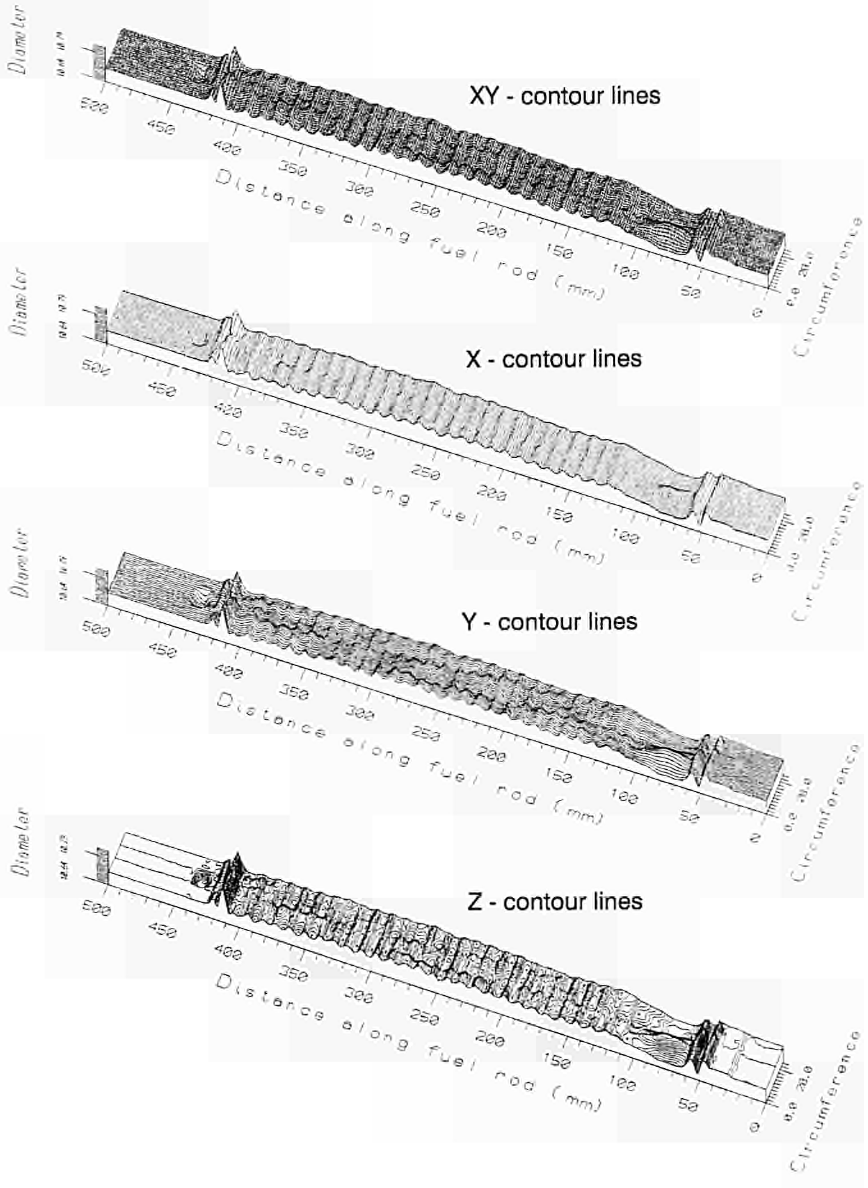
A new measurement method and evaluation procedure for diameter and eddy current measurements on irradiated LWR fuel rods (in the HFR pool) was introduced /10/. **Fig. 11** shows a typical result from the evaluation of the diameter measurements.

Activities were started to integrate an oxide layer thickness measurement system into the underwater measurement system for LWR fuel rods.

### 3.1.2. Structural Materials Irradiation Testing

The extension of the operational life time of light water reactors requires investigations on the corrosion and mechanical behaviour of the structural materials in the core region and of the pressure vessel.
Irradiation proposals addressing the irradiation testing of various components, metal and ceramics samples under LWR and gas environment were prepared and discussed with potential clients.

**Fig. 11**
3D presentations of diameter measurements



At the 19th MPA Seminar at Stuttgart an overview on the HFR irradiation programmes and capabilities for irradiation testing of stainless steel /9/ was presented.

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## 3.2. FAST BREEDER REACTOR (FBR). FUEL AND STRUCTURAL MATERIAL IRRADIATIONS

During the late 70's and early 80's, several international R&D programmes were initiated, each with their own goal of qualifying various FBR fuels and materials under normal and off-normal conditions.

The HFR played an important role in performing many experiments for the German and Dutch programmes. In the late 80's, due to the apparent measures being taken to achieve specific goals including acceptable safety features, within acceptable economic constraints, a five-nations collaboration to develop a demonstration European Fast Breeder Reactor (EFR) was made. The objectives of the EFR were: capital and generating costs should be comparable with competing PWR's; availability and reliability should be similarly comparable; construction should be assured within a defined time-scale; and there should be a minimum extrapolation to a commercial plant. As such, the existing objectives of the FBR experimental programme at the HFR, remained essentially the same. However, towards the end of 1992, there was a general reduction in FBR support in Europe, resulting first in the UK withdrawal from the project in 1993 and more critically, the announcement by the German Ministry of Science and Technology to reduce immediately all EFR R&D, resulting in the decision by KfK (principal sponsors of the HFR FBR programme) to curtail all FBR activities at the end of 1994. As such, all the remaining KfK FBR experiments at HFR were completed in 1993. Despite this, some high quality work was performed, with 4 experiments, using 7 fuel pins, being completed with successful outcome. Despite the termination of this particular programme, preparations began on the irradiation of transuranium fuels, as part of a multinational (KfK, CEA, ITE) project on transmutation and burn-up of actinides and fission products. Meanwhile, the irradiation programme on advanced fuels, sponsored by the Institute for Transuranium Elements of the JRC at Karlsruhe, saw the successful completion of the last nitride fuel experiment and the start of the POMPEI experiment, which includes fuel pellets containing $^{99}$Tc, as part of a pathfinding transmutation study.

### 3.2.1. Fuel Irradiations

Fast reactor fuel experiments carried out in the HFR Petten fall into two categories.

- *Transient Tests*

The investigation of fast reactor fuel pin behaviour under transient reactor conditions: features investigated include start-up behaviour, power cycling and ramping, fuel melting, transient overpower (TOP) and simulated loss-of-flow (LOF) behaviour. Both fresh and pre-irradiated fuel pins are used.

- *Advanced Fuel Irradiations*

These concern investigations into the operational behaviour of dense (nitride) fast breeder fuels and more fundamental research on fission product kinetics in UO2 fuel. This group of experiments is part of the JRC Specific Programme on Nuclear Fuels and Actinide Research, and has been extended to include transmutation studies with regard to long-term disposal of radioactive wastes.

## Transient Tests

During the reporting period four experiments were completed, involving the irradiation testing of 7 fuel pins.

### POUSSIX (project KAKADU)

The aim of the POUSSIX experiment was to perform a 150% overpower transient on a high burn-up fuel pin, in order to demonstrate that towards the end-of-life in an FBR, a fuel pin can tolerate excessive transients due to plausible accident or off-normal scenarios. As such, 2 pre-irradiated fuel pins, which had been irradiated to over 10 at.% burn-up in the French PHENIX fast reactor, were transported to Petten. To perform such experiments, the HFR is equipped with facilities that can receive highly contaminated fuel pins, decontaminate them using a special electro-chemical process, remotely load the pins into a double-containment capsule, which is then sodium-filled and weld-sealed remotely and semi-automatically in the special EUROS-cell, and then transferred to the HFR for irradiation. During the irradiation phase in the PHENIX reactor, there is a build-up of poisons in the fuel which reduces by neutron absorption the linear fissile power of that pin. In particular, the radioisotope $^{149}$Sm, is responsible for the power depression within the pin. Hence, prior to performing the transient in the Pool Side Facility (PSF) of the HFR, a pre-conditioning phase is carried out whereby the fuel pin is kept at constant power over a number of days, whilst most of the $^{149}$Sm is burned away, **see fig. 12**. This effect can only be performed on the PSF facility and not in-core, as whilst the amount of $^{149}$Sm is decreasing, the irradiation capsule is slowly withdrawn on the PSF trolley, i.e. it is slowly removed from the reactor core, thus reducing the prevailing flux conditions. The actual

**Fig. 12**
Pre-burning of $^{149}$Sm in PSF

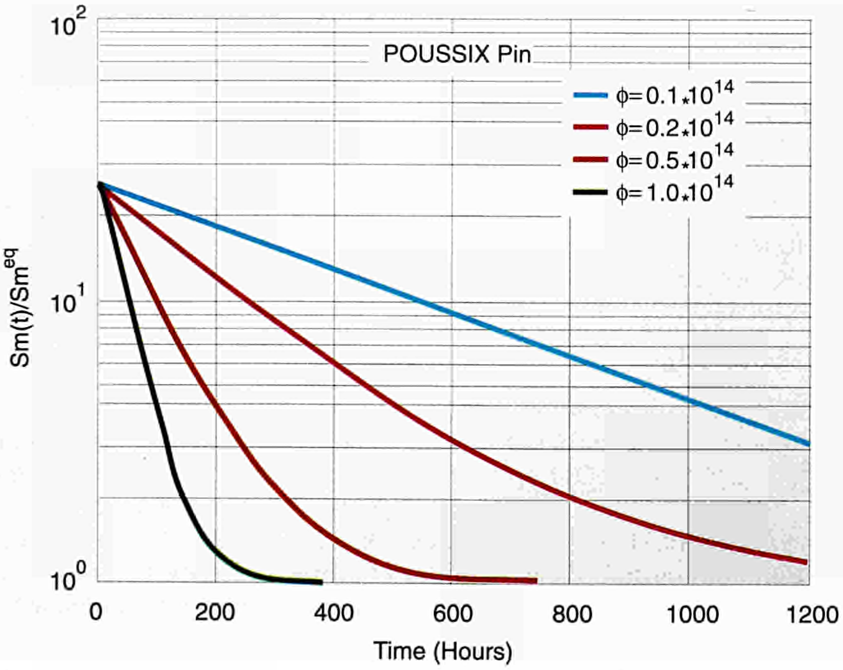
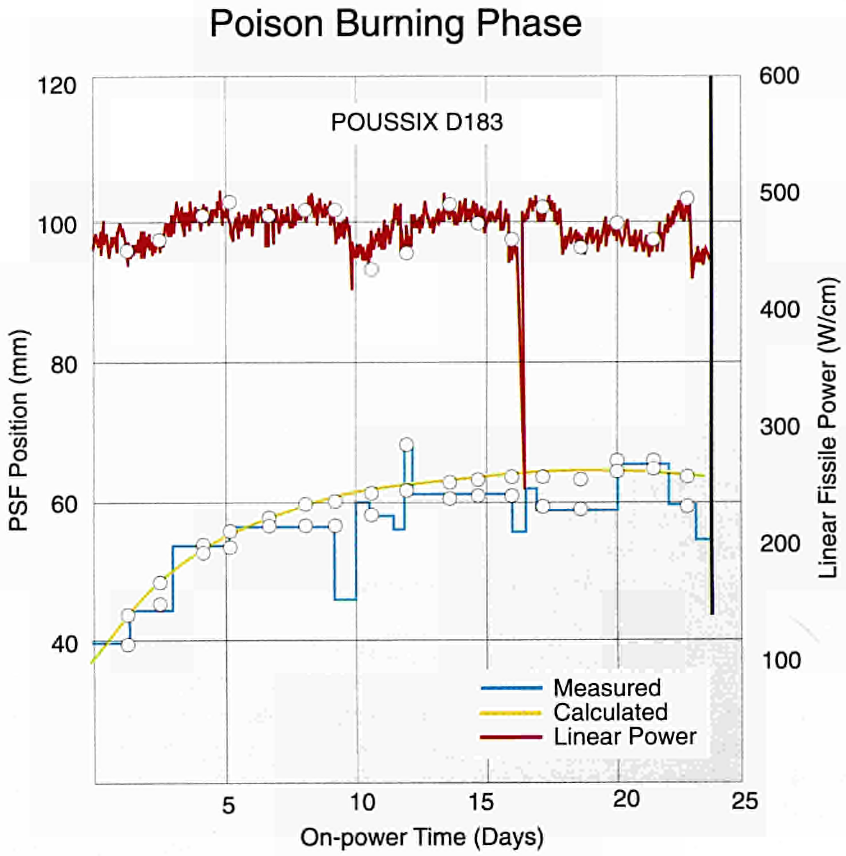


**Fig. 13**
Plot comparing the measured and calculated PSF position during the poison burning phase for POUSSIX



procedure is first calculated using the available, sophisticated nuclear physics codes. A comparison between the calculated withdrawal procedure and that performed is shown in **fig. 13**. Following this burn-up phase, the subsequent transient was performed, whereby a peak linear power of 700 W/cm was achieved compared to the 450 W/cm nominal power during burning and just prior to the transient, i.e. an overpower transient of 156%.

POTOM

The aim of the POTOM series of experiments is to determine the power at which melting of the fuel first occurs, as a function of material composition (Pu-content), fuel type (homogeneous/heterogeneous) and duration of pre-conditioning. Following 5 POTOM experiments, reported in previous annual reports, and one OPOST (overpower steady state) experiment, the sixth and final POTOM experiment was completed during 1993. The series of experiments has produced a wealth of important data, giving confidence to the predictions of the code modellers in designing FBR fuel. A summary of these results is indicated in **fig. 14,** /1/.

RELIEF

The experiment aims to study, by means of in-pile measurement, the differential and absolute fuel and cladding axial displacements during operational transients. In previous years three experiments have been completed and reported. During 1993, the fourth and fifth (final) experiments were completed. The results have complemented the results calculated by the fuel designer's code.

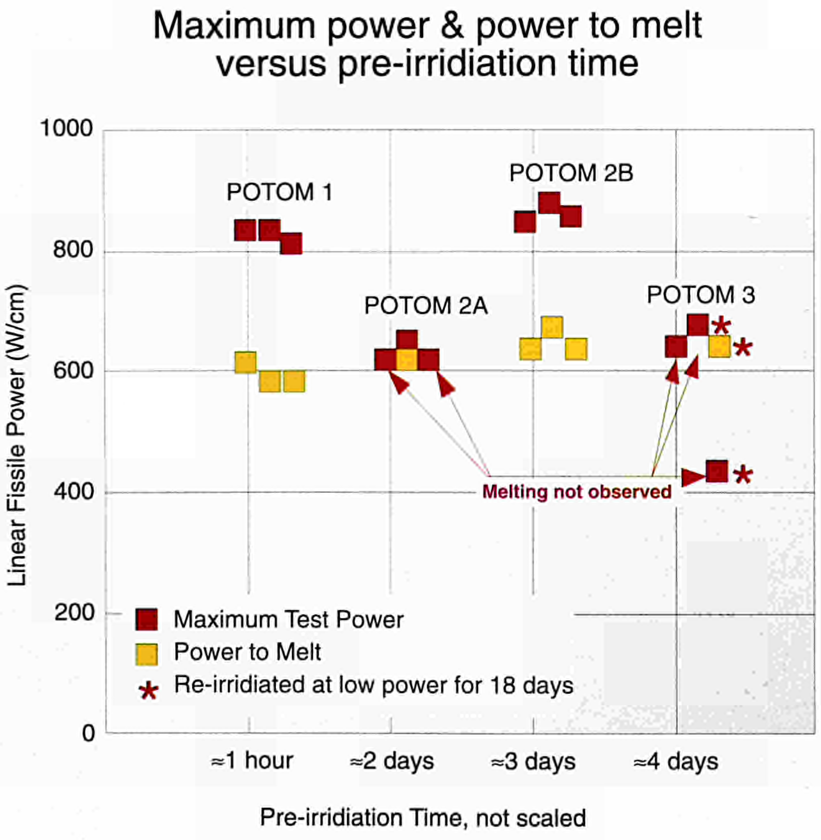
Advanced Fuel Irradiations

Mixed nitride (U,Pu)N is the reference fuel for a fast reactor cycle with a denser optimised fuel than the currently used mixed oxide.
The programme on "Optimisation of Dense Fuels" at the Institute for Transuranium Elements (ITE), Karlsruhe, aims at optimising "pure" mixed nitrides for high burn-up fast reactors. Part of this program involves the irradiation testing of fuel in the HFR.

NILOC

The fourth NILOC experiment was completed at the start of 1993. The experiment NILOC 4, irradiated 3 nitride pins, of "fat" proportions. As such, peak linear fissile powers of up to 960 W/cm were reached, with no

**Fig. 14**
POTOM experiments



apparent detrimental effect on the fuel pin behaviour. The irradiation period was one reactor cycle, thus attaining 0.5 at.% burn-up.

POMPEI

The POMPEI experiment started irradiation in cycle 93.08. Its aim is to irradiate thin vertically placed discs of $UO_2$ to very high burn-up (>20 at. % bu). The fuel pin also includes 3 pellets containing 100% Tc, 50:50% Tc:Ru and 20:80%, Tc:Ru. The 3 pellets are part of a pathfinding irradiation to investigate transmutation of actinides by radiation in reactors, such as the HFR. The experiment is planned to end in summer 1994.

### 3.2.2. Structural Material Irradiations

The bulk of these HFR experiments falls within the scope of fast reactor safety programmes. Irradiations in the HFR Petten are carried out to stringent specifications concerning specimen temperature and neutron fluence. They have supplied accurate information of material embrittlement by helium formation and fast neutron displacements.

SINAS/FBR

This irradiation programme will provide sufficient specimens for continuous cycling and creep-fatigue post-irradiation testing. The irradiation and testing conditions will be as close as possible to the conditions of the EFR (European Fast Reactor) above-core structures. The objectives of this work are to provide data on creep-fatigue properties of irradiated stainless steel type 316 L(N) for the EFR design data-base, and to verify the creep-fatigue interaction models.

In the reporting period the following progress was made.
The irradiation conditions of this experiment were 823 K at a very low dpa (one reactor cycle in the H8 position) and the irradiation took place in a TRIO-131 with a double container. This was required in order to obtain the temperature of 823 K at a peripherical reactor position.
Two legs of the TRIO contained fatigue specimens and the third leg tensile-creep specimens. Six legs were irradiated in position H8 for one cycle (cycles 93.03 and 93.06). Post-irradiation examination started in October 1993.

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## 3.3. HIGH TEMPERATURE REACTOR (HTR). FUEL AND GRAPHITE IRRADIATIONS

Although governmental funding by BMFT (Bundesministerium für Forschung und Technologie) of R&D for High Temperature Reactor (HTR) Technology in Germany has been brought to an end in 1992, committed irradiation tests for a commercial HTR-Modul reactor were continued in 1993, and will be terminated as agreed upon **(table 3)**. The typical materials, which are being tested at the HFR Petten for the HTR-Modul /1,2/, are:

(a) spherical fuel elements with low-enriched uranium ($UO_2$) TRISO coated particles, and
(b) graphite as a predominant core structural and fuel element matrix material.

In more than 25 years, the outstanding qualification of the HFR as a test bed for HTR materials has convincingly been demonstrated /1/. The entire field for HTR in-pile testing is covered by the available irradiation facilities. Work for other R&D programmes on HTR than for Germany has been performed in the past, and is being performed at present.
Under the "Umbrella Agreement on the collaboration in HTR R&D development within the civil programme" between Germany and USA an irradiation test on fuel rods of the prismatic fuel element of the US-HTGR has been performed at the HFR Petten /2,4/. In 1993, the draft final irradiation report was issued in collaboration with ORNL. The final revision of the irradiation report can be issued in 1994 after the planned completion of the post-irradiation examinations at KFA Jülich **(table 3)**.

### 3.3.1. Fuel Element Irradiations

Proof tests of fuel elements for the German R&D Programme on HTR

High Temperature Reactor (HTR) fuel testing is being performed at the HFR Petten on reference coated particle systems and "near-to-production" spherical fuel elements for the German $UO_2$ low-enriched uranium (LEU) fuel cycle /4/. The fuel elements, the reference 60 mm diameter spheres with LEU-TRISO coated particles, as developed by NUKEM/HOBEG for all future HTR applications, are being tested under conditions as close as reasonably achievable for HTR-Modul power plant characteristics, including simulation of multiple-pass fuel reloading systems.
Eight "near-to-production" fuel elements are being tested at the HFR Petten since 1990 in two identical proof tests. The main objectives of these tests are the confirmation of low coated particle failure rates caused by temperature, temperature transients/cycling, burn-up and/or by fast neutron damage, and the confirmation of low free heavy metal (uranium and thorium) contamination of the fuel element matrix material by natural impurities and/or by defective coated particles. Therefore, the irradiation capsules are operated with specially developed SWEEP-LOOPS for on-line measurements of the release of volatile fission products under a wide R/B (Release to Birth rate) range ($10^{-10}$< R/B <$10^{-1}$), as well as for on-line gas chromatographical analysis of the purge gas.

The irradiation of the first reference test, which started in 1990, was successfully terminated in 1993. During an irradiation period of 26 HFR cycles, equivalent to 633.55 full power days, 17 HTR-Modul multiple-pass fuel loading conditions and four temperature transients were simulated /2,5/. The multiple-pass simulation comprised the irradiation at 1073 and 1273 K central fuel element temperature at defined intervals. Temperature transients of up to 1473 K for periods of 5 hours were performed during the 5th, 9th, 11th and 17th Modul cycle. The achieved neutron fluence (E>0.1 MeV) ranged from 3.2 to $4.8 \times 10^{25}$ $m^{-2}$ and the fissile burn-up ranged from 7.2 to 9.7% fima.

On-line fission gas release measurements were performed daily. The results of these measurements revealed that:
(a) not a single coated particle failed during irradiation,
(b) the low free heavy metal (uranium and thorium) contamination of the fuel elements was confirmed by a low fractional fission gas release of $<10^{-9}$ at BOL (beginning of life).

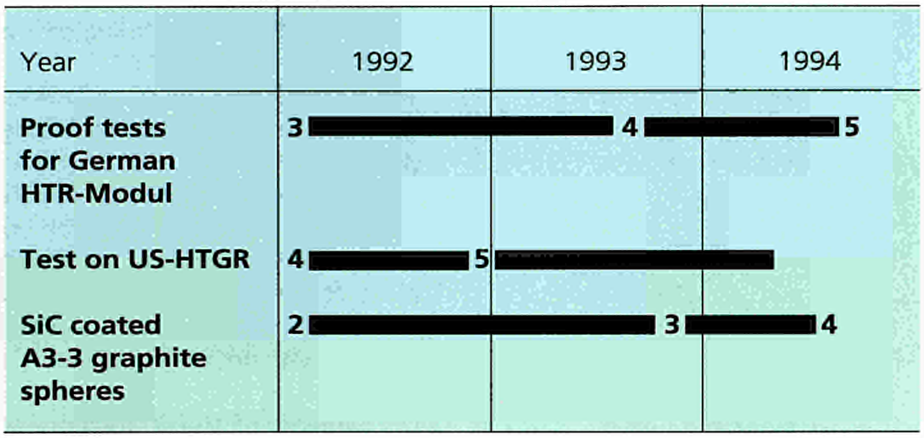
The fission gas release behaviour at increased water vapour concentrations in the purge gas, simulating accidental conditions, was investigated during the 14th and 17th Modul cycle in one capsule which contained two defective coated particles (failure caused during manufacture) /2/. The partial pressure of water in the purge gas of these tests ranged between 2 and 20 mbar. Although evaluation of the experimental data is not complete, it can be concluded already now, that the moisture effect on the release of volatile fission products (Kr, Xe and I) during a water ingress accident can not be neglected.

Dismantling of the irradiation rig and recovery of the fuel elements is planned for 1994 at the Petten hot cells. The recovered fuel elements will be send back to KFA Jülich for post-irradiation examinations. Final reporting on the experiment will be done as soon as metrology and gamma scan data are available **(table 3)**.

The irradiation of the second proof test for the HTR-Modul, also with four fuel elements in three independently controlled capsules, continued successfully in 1993. Fifteen Modul cycles were completed after nineteen HFR cycles by the end of 1993. The fractional fission gas release data still correspond with the heavy metal contamination of the graphite matrix material. The cumulative burn-up was 7.7% fima and the cumulative neutron fluence was $3.6 \times 10^{25} m^{-2}$ (E>0.1 MeV) after 472 full power days. Irradiation progress reports were issued cycle by cycle. The irradiation is planned to be terminated in 1994 after 23 HFR cycles. Dismantling and transport of the fuel elements to KFA Jülich will be performed together with the specimens of the first proof test in 1994 **(table 3)**.

Irradiation of SiC-coated A3-3 graphite spheres

Protection of spherical fuel elements by means of a corrosion resistant SiC-layer for concepts of "inherent safe HTR's" has been proposed by KFA Jülich.
The irradiation behaviour of such SiC-coated spherical fuel elements will firstly be tested on A3-3 graphite spheres without coated fuel particles. Therefore, on request of KFA Jülich, an irradiation experiment has been designed for testing seven specimens at the HFR Petten in the temperature range from 873 K to
1273 K up to a fast neutron fluence of $2.6 \times 10^{25} m^{-2}$ (E >0.1 MeV). One out-of the seven specimens will be left uncoated and serves as reference specimen. The in-pile test is planned for a period of four cycles, starting by the end of 1994 **(table 3)**.



**Legend:**
1 Design & calculation
2 Manufacture and commissioning
3 Irradiation
4 Dismantling & PIE
5 Final report

**Table 3**
HTR fuel irradiation experiments.
Survey of present and future activities

### 3.3.2. Graphite Irradiations

A huge campaign for the development and qualification programme of a graphite to provide a design base to the German High Temperature Reactor Programme was launched about twenty years ago. The irradiation programme is now almost completed.

The irradiation capsules can contain unstressed samples (fundamental properties) or creep specimens under tensile or compressive stress. Samples have been irradiated, in both cases, in three to four fluence steps, with intermediate measurements of their properties.

Fundamental properties graphite programme

The objective of this investigation has been the characterization of reflector and matrix graphites covering all relevant material properties. One experiment is presently under irradiation (D85-63) concerning reflector material being irradiated at 873 K and aiming at a final fluence value of $1.2 \times 10^{26} m^{-2}$ (EDN)*. Two additional experiments will complete the irradiation campaign, as shown in the summary of **table 4.**

**Table 4**
Graphite fundamental properties – status of experiments

| Exp. number | Irradiation Temperature | Total Fluence (EDN) | Status |
|---|---|---|---|
| D85-63 | 873 K | 1.2 x $10^{26}$ $m^{-2}$ | under irradiation; fluence reached : 7.3x$10^{25}$ $m^{-2}$ |
| D85-64 | 723 K | 1 x $10^{26}$ $m^{-2}$ | ready; waiting for samples |
| D85-67 | 1023 K | 4 x $10^{25}$ $m^{-2}$ | ready; waiting for samples |

Graphite creep experiments

Irradiation creep which relieves stresses, is an important parameter in the design of High Temperature Reactors, where relevant stresses can be generated due to thermal and neutron flux loads.

Special devices have been designed and employed at HFR, allowing irradiation under stress of various grades of graphite up to very high fluences (1x$10^{26}$ $m^{-2}$ EDN) and in a wide temperature range (570 to 1170 K). Creep measurements have taken place out-of-pile at intervals of irradiation /6/. Experiments have also been performed in stress mode change (tensile to compressive or viceversa) and/or in temperature mode change.

The design of the experiment D156-70,-71,-72 which should conclude the irradiation campaign, is ready.A decision of the sponsor on the execution of the experiment is waited for.

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* traditional graphite exposure unit ("Equivalent DIDO Nickel")

## 3.4. FUSION REACTOR MATERIAL IRRADIATIONS

Fusion is regarded as one of the promising long-term energy options. Important efforts are ongoing worldwide to promote this option. Whereas the larger share of the resources is still spent on programmes to demonstrate the physical feasibility, it is meanwhile fully realized that it is essential to expand the effort on technology. The HFR plays a major role as test bed for fusion materials irradiations since a long time. /4,5,6,7/.

The different fusion related projects are incorporated into the European Fusion Technology Programme and form part of the R&D work towards the NET/ITER design and towards future demonstration plants (DEMO).

At present irradiation experiments are being performed to investigate creep, fatigue and crack growth of candidate first wall protection materials as graphite and carbon reinforced composites (CFCs) and structural materials as austenitic steels, MANET, SiC/SiC composites and vanadium alloys.
Candidate blanket breeder materials are being tested more and more with special emphasis on prospective operating conditions of ITER shielding blankets and blanket concepts for DEMO.

Recently attention is also devoted to investigation of irradiation effects on whole components, like the in vessel inspection system of JET (consisting of cameras, lenses, cables, motors, etc.) and the magnet insulation system of the same machine.

### 3.4.1. Irradiation of First Wall Materials

Experiments on first wall materials are sponsored by:
- Joint Research Centre, Institute for Advanced Materials, involved in investigations on creep behaviour of steels and on properties of SiC-SiC composites
- ECN, involved in studies on mechanical properties changes in steels
- German institutions (KfK, KFA), involved in studies on properties of optimized MANET steels and ceramic first wall and insulator materials

### 3.4.1.1.Experiments for the Specific Programme of the Joint Research Centre

Advanced Low Activation Materials

It is of great importance to minimize the short term activation level by developing structural materials made of elements having low post-irradiation activation. Low Activation Materials (LAMs) include elementally tailored steels, vanadium alloys and advanced materials.

The group of advanced materials showing activation characteristics which could be attractive for reducing the public safety risk in case of various accident scenarios and for simplifying remote maintenance operation includes SiC-SiC
composites. The Institute for Advanced Materials, in collaboration with other organisations, has launched a campaign to investigate the basic

properties of such materials, and changes of properties due to irradiation. Bending tests, fibre pull-out, fractography, thermal conductivity measurements will be performed on samples before and after irradiation. Sample holders have been designed and are presently under construction to host SiC-SiC samples to be irradiated at 1023 K at various fluence steps (1.2 and 5 dpa). Details on the experiment are given in **table 5**.

| Experiment | Number | Material | Samples dimensions (mm) | Number of samples | Temp. (K) | dpa | Tests | Status |
|---|---|---|---|---|---|---|---|---|
| SICOMORO (Silicon Carbide Fibre Reinforced Composites Irradiation) | E 274-01,-02,-03 | SiC-SiC (Composition in table 6) | 80x8x1.2 in each s.h. | 8 | 1023 | 1.2, 5 | P.I.E. bending, fibre pull-out | under assembly |
| TRIESTE | E 167-80 | 316L,<br>AMCR,<br>US316 | ø2x59 | 49 | 370 | up to 5 | Creep measurement during irradiation, load during irradiation: 100,200,300 MPa | under irradiation |
| TRIESTE | E 167-90 | 316 L welded specimens | ø2x59 | 49 | 370 | up to 5 | Creep measurement during irradiation, load during irradiation: 100,200,300 MPa | ready; irradiation start in 94.03 |
| TRIESTE | E 167-100 | 316 L welded specimens | ø2x59 | 49 | 650 | up to 5 | Creep measurement during irradiation, load during irradiation: 100,200,300 MPa | under construction |

**Table 5**
Summary of experiments on first wall structural materials, sponsored by IAM

**Table 6**
Material composition (ppm) (SICOMORO)

| Element | ppm |
|---|---|
| Na | 13.4 |
| Cl | 317. |
| Al | 1020. |
| Mn | 3.05 |
| W | 0.5 |
| Sm | < 0.001 |
| U | < 0.040 |
| Mo | < 0.2 |
| Yb | < 0.01 |
| As | 0.016 |
| Sb | 0.055 |
| La | 0.011 |
| Au | 572. |
| Cd | < 0.013 |
| Ta | < 0.01 |
| Fe | 26. |
| Co | 0.094 |
| Ce | < 0.15 |
| Rb | < 0.2 |
| Hf | < 0.01 |
| Eu | < 0.004 |
| Cr | 0.0031 |
| Se | < 0.3 |
| Cs | < 0.015 |
| Sc | 0.001 |
| Ba | 2 |
| Lu | < 0.002 |
| SiC | Balance |

Creep Testing of Fusion Materials

The Institute for Advanced Materials is involved since years in the characterisation of the creep behaviour of candidate structural materials.

In particular two different facilities have been designed and operated for years to study the irradiation effects on creep behaviour: one facility allowing on-line creep measurements /1/, the second, reloadable, allowing intermittent creep measurements in hot cells, between irradiation steps.

The present programme, under execution, foresees irradiation of reference steels like 316L, AMCR, US316 at low temperature (< 273 K). Moreover irradiation of welded materials is also foreseen with the same boundary conditions and at higher temperature (650 K); loads are in the range 100-300 MPa.

A summary of the situation can be found in **table 5**.

### 3.4.1.2. Experiments for ECN

ECN participates in the frame of the Commission's cost shared action in the European Fusion Reactor Materials Programme. The properties of a number of candidate materials are determined and presented as a comparison between irradiated and non-irradiated specimens with identical heat treatment. Crack propagation and fracture toughness are the main areas of interest. In order to save irradiation space and limit the temperature gradients in the specimens caused by gamma heating, most specimens are of the compact tension type.

SIWAS

This irradiation accommodates NET construction material. 40 CT specimens, 10 tensile and 20 fatigue are currently under irradiation in core position E7, at reactor ambient temperature (about 360K). The required damage is 5 dpa. The experiment takes place in a REFA 170 and the specimens are in contact with reactor coolant water. Irradiation series 139-665 started in cycle 93.11 and will be terminated in cycle 94.04.

SINAS

This experiment consists of 8 sample holders of NET construction material, with 10 CT specimens in each holder. The specimens are in contact with liquid metal, sodium. This is necessary to minimise the temperature gradients within the CT specimens. The irradiation temperature is 525 K at different fluence levels (irradiation positions F8 and F2) for 5 dpa and 0.3 dpa. Irradiations series 139-697-698 started in cycle 92.04 and finished in cycle 93.05 whereas series 139-699 started in cycle 92.08 and will finish in cycle 94.06.

In addition to the above mentioned experiments ECN has notably increased in the recent past its involvement in the European Fusion Programme for the qualification of first wall structural materials.

A huge irradiation campaign has been launched for the characterisation of mechanical properties of 316 steels, and low activation materials (MANET and optimized MANET steels). Post-irradiation examinations include tensile, charpy and fracture toughness tests /8/. Details on the materials investigated are given in **tables 7 and 8**.

**Table 7**
Material composition (wt%) of samples irradiated in the FURIAE experiment

| Element | Material | |
|---|---|---|
| | Type 316 K heat 13824 | Type 316 CL heat 11477 |
| C | 0.026 | 0.02 |
| Ni | 12.50 | 12.50 |
| Cr | 17.39 | 17.34 |
| Mn | 2.06 | 1.80 |
| Cu | 0.04 | 0.12 |
| Si | 0.15 | 0.32 |
| S | 0.002 | 0.0006 |
| P | 0.024 | 0.02 |
| $N_2$ | 0.0670 | 0.08 |
| Co | 0.05 | 0.03 |
| Ti | 0.01 | 0.008 |
| B | 0.0004 | 0.0014 |
| Mo | 2.43 | 2.40 |
| Nb | 0.01 | 0.042 |
| Ta | 0.002 | 0.005 |
| Fe | balance | balance |

Specimens are being irradiated in a wide temperature range (353 - 700 K) at various damage levels (0.5 up to 2.5 dpa). Six different devices and a special insert for TRIO capsules /1/ have been designed to face this massive and diversified irradiation request. The characteristics of the devices are summarised in **table 9. Fig. 15** shows the TRIMURTI inserts with FURIAE/MANIA type sample holders.

**Table 10** presents the status of the irradiation campaign (experiments performed in 1993 and experiments planned).

| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material | MANET I 12 mm | MANET II 20 mm | Modified 9% Cr (E) | HT-9 | Modified 9% Cr (F) | LA12TaLC | LA7 | MANET I rod | MANET II rod | MANET II 8mm | US-1 |
| C | 0.14 | 0.10 | 0.09 | 0.20 | 0.105 | 0.11 | 0.16 | 0.13 | 0.11 | 0.10 | 0.20 |
| Si | 0.37 | 0.14 | 0.31 | 0.28 | 0.43 | 0.03 | 0.44 | 0.37 | 0.27 | 0.18 | 0.13 |
| Mn | 0.76 | 0.75 | 0.46 | 0.51 | 0.38 | 0.99 | 0.77 | 0.82 | 0.94 | 0.76 | 0.47 |
| P | 0.005 | 0.005 | 0.011 | 0.002 | 0.009 | < 0.005 | 0.012 | 0.005 | 0.005 | 0.004 | 0.010 |
| S | 0.004 | 0.0045 | 0.002 | 0.005 | 0.0025 | 0.005 | 0.01 | 0.004 | 0.004 | 0.005 | 0.004 |
| Cr | 10.8 | 10.3 | 8.68 | 11.86 | 8.26 | 9.10 | 11.20 | 10.6 | 10.3 | 10.4 | 11.97 |
| Mo | 0.77 | 0.57 | 0.92 | 1.02 | 0.95 |  |  | 0.77 | 0.56 | 0.58 | 1.04 |
| Ni | 0.92 | 0.65 | 0.12 | 0.54 |  |  |  | 0.80 | 0.62 | 0.65 | 1.14 |
| Al | 0.054 | 0.004 | 0.008 | 0.002 | < 0.003 |  |  | 0.054 | 0.0034 | 0.007 | 0.017 |
| V | 0.20 | 0.19 | 0.21 | 0.30 | 0.075 | 0.38 | 0.25 | 0.22 | 0.20 | 0.21 | 0.53 |
| Nb | 0.16 | 0.14 | 0.09 | < 0.01 | 0.20 |  |  | 0.16 | 0.15 | 0.16 | 0.015 |
| Ti |  |  | 0.004 | < 0.01 | 0.024 |  |  |  |  |  | 0.003 |
| Co | 0.01 | 0.007 | 0.01 | 0.13 |  |  |  | 0.01 | 0.006 | 0.005 | 0.015 |
| Cu | 0.015 | 0.01 | 0.05 | 0.01 |  |  |  | 0.015 | 0.007 | 0.01 | 0.05 |
| B | 0.0085 | 0.075 |  |  | 0.08 |  |  | 0.0085 | 0.0089 | 0.0075 | 0.001 |
| W |  |  |  | 0.54 |  | 0.76 | 2.95 |  |  |  | 0.53 |
| Zr | 0.059 | 0.028 |  |  | < 0.02 |  |  | 0.053 | 0.009 | 0.008 | 0.001 |
| N | 0.02 | 0.031 | 0.049 | 0.0014 |  | 0.0094 | 0.065 | 0.02 | 0.026 | 0.032 | 0.016 |
| Ta |  |  |  | < 0.01 | 0.055 | 0.07 |  |  |  |  |  |
| As |  | 0.01 |  |  |  |  |  |  |  |  |  |
| Sn |  | 0.001 |  |  |  |  |  |  |  |  | 0.001 |
| Sb |  | 0.0004 |  |  | 0.008 |  |  |  |  |  |  |
| O |  |  |  |  |  |  |  |  |  |  | 0.007 |
| Fe | bal. | bal. | bal. | bal. | bal. | bal. | bal. | bal. | bal. | bal. | bal. |

**Table 8**
Chemical composition in weight % of materials investigated in the experiments CATETO, CHARIOT, ILAS, MANIA, SIRIO

### 3.4.1.3.Experiments for KfK and KFA

Irradiation of optimized MANET steels

The Nuclear Research Centre KfK (Kernforschungszentrum Karlsruhe) is investigating the irradiation behaviour of martensitic steel DIN 1.4914, identified as MANET steel for use as first wall structural material.

Seven "optimized" versions of the steel have been prepared by KfK, as illustrated in **table 11** and it is foreseen to irradiate the specimens (charpy type, 3 x 4 x 27 mm) at five different temperatures (523, 573, 623, 673, 723 K) and at three fluence values (0.2, 0.8 and 2.4 dpa).

A special sample holder type, named MANITU (Manet irradiation for fusion applications), has been designed. It allows the irradiation of up to 180 charpy samples at 5 different temperatures. The samples are housed in an aluminium pipe in five layers: each layer is separated by means of insulating materials ($ZrO_2$ plates). Appropriate choice of filler elements

| DEVICE | CHARACTERISTICS |
|---|---|
| TRIMURTI<br>(Trio modified for fusion materials and irradiations) | Special insert for channels of modified TRIO capsules /2/; it allows simultaneous independent irradiation of 3 sample holders per TRIO channel.<br>It is available in two versions : - "wet" for low temperature irradiations (350K)<br>- "dry" for higher temperatures<br>Sample holders which must be used with this insert:<br>FURIAE or MANIA type (see below) |
| FURIAE<br>(Future reactor materials irradiations for ECN) or<br>MANIA<br>(MANET irradiations) | Irradiation of tensile specimens (9 miniaturized specimens : ø 6, l=45 mm) /8/<br>Temperature range : 350 K (in "wet" TRIMURTI) or 550 - 700 K (in "dry" TRIMURTI)<br>$\Phi_{fast}$ (E > 0.1 MeV) in the range : $1.8 - 2.7 \times 10^{18}\ m^{-2}\ s^{-1}$<br>Occupation : 1 TRIMURTI channel (max. 9 sample holders in a TRIO capsule /1/) |
| ILAS<br>(Irradiation of low activation materials) | Sample holder for irradiation of tensile (miniaturized specimens : ø 6, l=45 mm)<br>and low cycle fatigue specimens (miniaturized specimens : ø 6, l=45 mm)<br>Total number of specimens : 50<br>Temperature range : 530 - 660 K<br>$\Phi_{fast}$ (E > 0.1 MeV) : $\sim 2.44 \times 10^{18}\ m^{-2}\ s^{-1}$ |
| CATETO<br>(Compact tension specimens irradiation) or<br>CHARIOT type<br>(Charpy and compact tension specimens irradiation) | Irradiation of compact tension (29 x 27 x 10 mm)<br>and charpy specimens (3 x 4 x 27.5 mm)<br>Total number of samples : 14 CT; 40 charpy<br>$\Phi_{fast}$ (E > 0.1 MeV) : $\sim 1.8 \times 10^{18}\ m^{-2}\ s^{-1}$<br>Occupation : 1 channel in a TRIO capsule |
| SIRIO<br>(Shielded irradiations) | Sample holder to irradiate 6 miniaturized tensile specimens (ø 6, l=45 mm) surrounded by a $B_4C$ shield, to limit He production and thus He embrittlement due to thermal neutrons interactions<br>Temperature range : 523 - 623 K<br>$\Phi_{fast}$ (E > 0.1 Mev) : $\sim 2.7 \times 10^{18}\ m^{-2}\ s^{-1}$<br>Occupation : 1 channel in a modified TRIO 131 capsule ("wet" TRIO) |

**Table 9**
Characteristics of irradiation devices

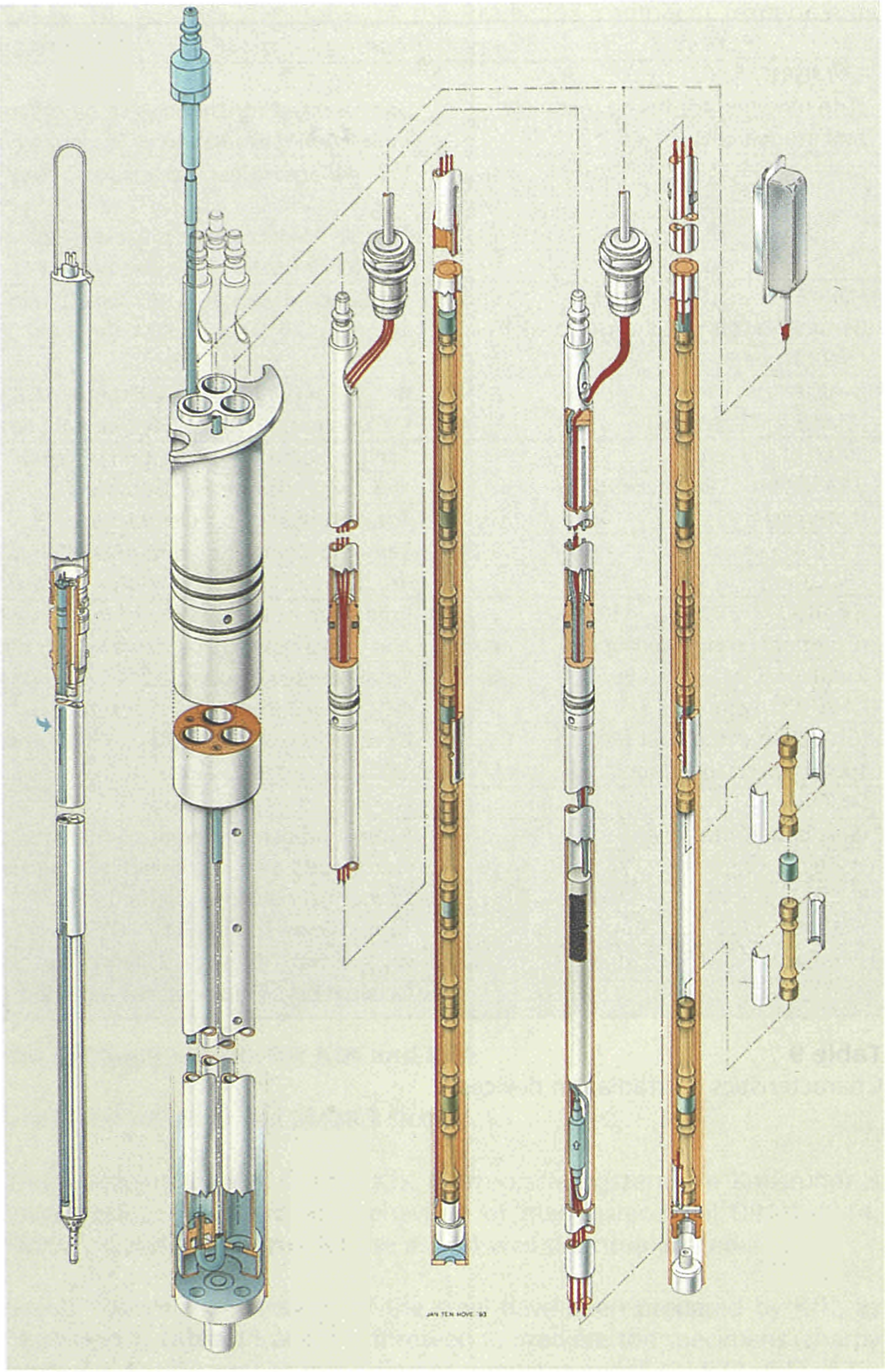


**Fig. 15**
TRIMURTI inserts with
FURIAE/MANIA type sample holders

| Experiments performed | | | | | | |
|---|---|---|---|---|---|---|
| **Experiment / Code** | | **Temperature (K)** | **dpa** | **Irradiation** | | **PIE** |
| | | | | **Start** | **End** | |
| MANIA | R 276-01 | 573 | 1.3 | 93.03 | 93.05 | tensile tests |
| | R 276-02 | 350 | 1.3 | 93.03 | 93.05 | done |
| FURIAE | R 275-01 | 690 | 0.5 | 93.01 | 93.01 | done |
| | R 275-02 | 690 | 1 | 93.01 | 93.02 | done |
| Experiments planned | | | | | | |
| **Experiment / Code** | | **Temperature (K)** | **dpa** | **Irradiation** | | **PIE** |
| | | | | **Start** | **End** | |
| MANIA | R 276-03 | 573 | 2.5 | 94.03 | 94.10 | tensile tests |
| | R 276-04 | 573 | 2.5 | 94.03 | 94.10 | |
| | R 276-05 | 573 | 2.5 | 94.03 | 94.10 | |
| | R 276-06 | 573 | 2.5 | 94.03 | 94.10 | |
| CATETO | R 278-01 | 573 | 1.5 | 94.02 | 94.06 | fracture toughness tests |
| | R 278-02 | 573 | 1.5 | 94.02 | 94.06 | |
| | R 278-03 | 573 | 1.5 | 94.02 | 94.06 | |
| | R 278-04 | 573 | 2.5 | 94.07 | 95.04 | |
| | R 278-05 | 573 | 2.5 | 94.07 | 95.04 | |
| | R 278-06 | 573 | 2.5 | 94.07 | 95.04 | |
| SIRIO | R 277-01 | 573 | 1.5 | 94.08 | 94.11 | tensile tests |
| | R 277-02 | 573 | 1.5 | 94.08 | 94.11 | |
| ILAS | R 285-01 | 573 | 2.5 | 94.05 | 95.01 | tensile and low cycle fatigue tests |
| | R 285-02 | 573 | 2.5 | 94.05 | 95.01 | |
| | R 285-03 | 573 | 2.5 | 94.01 | 95.08 | |
| CHARIOT | R 287-01 | 2.5 | 94.11 | 95.09 | | fracture toughness and charpy tests |
| | R 287-02 | 573 | 2.5 | 94.11 | 95.09 | |
| | R 287-03 | 573 | 2.5 | 94.11 | 95.09 | |

**Table 10**
Status of experiments

and stepped gas gaps guarantee the achievement of five different temperatures in the same holder.

A summary of the experiment characteristics is given in **table 12**.

Irradiation of ceramic first wall and insulators material

In the frame of the European Fusion Reactor Materials Research Programme different ceramics are investigated as candidate materials for the first wall protection of NET (project CERAM).

Experiment series 217 - 17-18-19 is part of a joint CEA Saclay and KFA programme. The aim of the experiment is to select plasma facing materials for NET/ITER. This experiment is a continuation of a previous series of experiments, but at lower irradiation temperatures, 873K, 1073K and 1273K and a target dose of 1 dpa.

Irradiation series 217 - 17 finished in cycle 93.01 in position G7. The irradiation temperature was 1073K and the dose 1 dpa. Irradiation series 217 - 18-19 started in cycle 93.03 and terminated in cycle 93.07. The irradiation temperature of 217 - 18 was 873K and 217 - 19 was 1273 K and the

| | MANET I | MANET II | Kasten charge 51482 | OPTIFER A | OPTIFER B | F82H | ORNL 3791 |
|---|---|---|---|---|---|---|---|
| C | 0.14 | 0.1 | 0.17 | 0.11-0.13 | 0.11-0.13 | 0.11 | 0.11 |
| Si | 0.37 | 0.14 | 0.34 | | | 0.09 | 0.21 |
| Mn | 0.76 | 0.79 | 0.54 | 0.4-0.8 | 0.4-0.8 | 0.07 | 0.44 |
| P | 0.005 | < 0.006 | 0.005 | < 0.005 | < 0.005 | 0.003 | 0.015 |
| S | 0.004 | < 0.007 | 0.005 | < 0.005 | < 0.005 | 0.0029 | 0.008 |
| Cr | 10.8 | 9.94 | 10.6 | 9.3-9.7 | 9.3-9.7 | 7.46 | 8.9 |
| Ni | 0.92 | 0.66 | 0.82 | | | 0.03 | < 0.01 |
| Mo | 0.77 | 0.59 | 0.49 | | | < 0.001 | 0.01 |
| V | 0.2 | 0.22 | 0.24 | 0.2-0.3 | 0.2-0.3 | 0.18 | 0.23 |
| Nb | 0.16 | 0.14 | 0.19 | | | 0.00005 | |
| Al | 0.054 | < 0.02 | 0.05 | | | 0.007 | 0.017 |
| B | 0.0085 | 0.007 | 0.0024 | 0.005-0.007 | 0.005-0.007 | 0.0003 | < 0.001 |
| N | 0.02 | 0.023 | 0.003 | 0.02-0.04 | 0.02-0.04 | 0.0044 | 0.0215 |
| Co | 0.01 | < 0.02 | 0.015 | | | 0.005 | 0.012 |
| Cu | 0.015 | < 0.01 | 0.01 | | | < 0.01 | 0.03 |
| Zr | 0.059 | 0.034 | | | | < 0.001 | |
| W | | | | 0.8-1.2 | 0.8-1.2 | 2.1 | 2.01 |
| Ta | | | | 0.1 | 0.1 | 0.03 | 0.06 |
| Ti | | | | | | 0.007 | < 0.01 |
| Fe | balance | balance | balance | balance | balance | balance | balance |

**Table 11**
Material composition (wt%)

| Experiment | | Number of samples | Specimens | Temperature (K) | dpa | Irradition start (cycle) | Irradiation end (cycle) | Status | P.I.E. |
|---|---|---|---|---|---|---|---|---|---|
| Name | Code | | | | | | | | |
| MANITU | D 271-01 | 180 | charpy (3 x 4 x 27 mm) | 523, 573, 623, 673, 723 | 0.2 | 94.03 | 94.04 | under assembly | charpy tests |
| | D 271-02 | 180 | charpy (3 x 4 x 27 mm) | 523, 573, 623, 673, 723 | 0.8 | 94.05 | 94.09 | | |
| | D 271-03 | 180 | charpy (3 x 4 x 27 mm) | 523, 573, 623, 673, 723 | 2.4 | 94.03 | 94.03 | | |

**Table 12**
Summary of experiment characteristics

accumulated dose 1 dpa. Transportation of specimens to KFA and CEA Saclay respectively will take place during the first quarter of 1994.

### 3.4.2. Irradiation of ceramic insulator materials at cryogenic temperatures

As part of the European Fusion Technology Programme it has become evident that present materials cannot provide the combination of low dielectric absorption and high resistance against thermal crack formation which is required to safely transmit 1MW/cw power at 145 GHz through a conventionally cooled window. Development of cryogenically cooled windows is currently under progress at KfK, because dielectric loss decreases and thermal conductivity increases strongly as temperature decreases

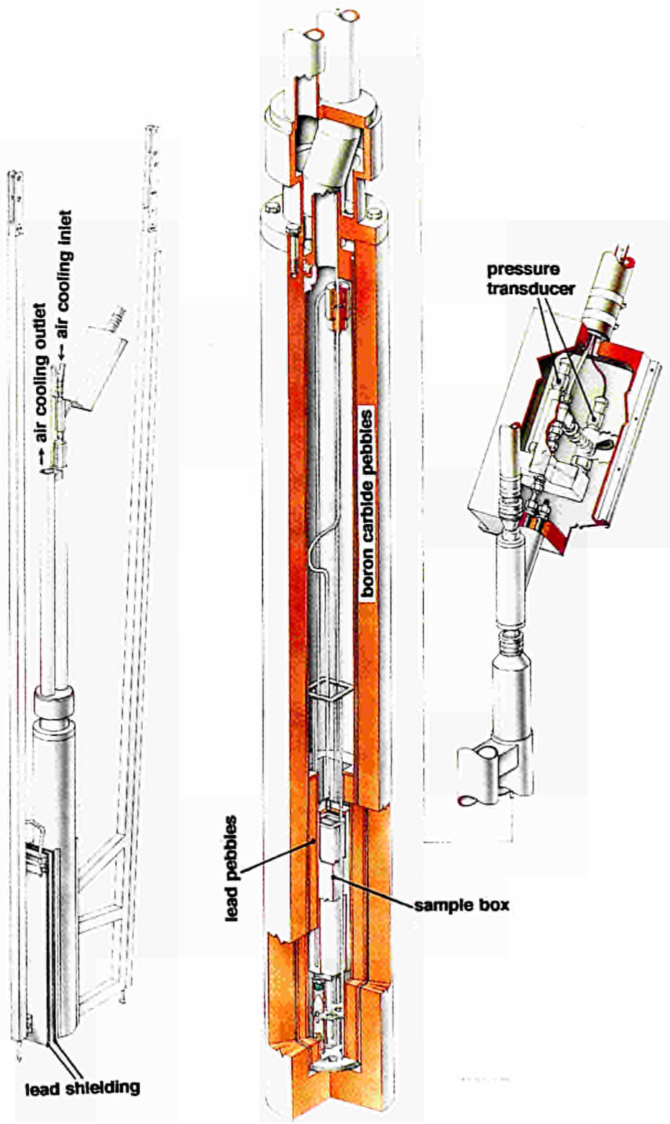


**Fig. 16**
EPIRO rig

below room temperature. The target is to define tolerable fluence levels by performing irradiations at $10^{16}$ to $10^{18}$ n/cm$^2$, E >0.1 MeV, at cryogenic temperatures. The materials to be irradiated are high purity single crystalline $Al_2O_3$ and $SiO_2$.

The design of the irradiation device started early 1993 and it will be finished in the first quarter of 1994. The irradiation will take place in the pool side facility in the first half of 1994.

### 3.4.3. Irradiation of Components

The development programme of the Joint European Torus (JET) includes a requirement for a thorough analysis of components behaviour under the severe loading conditions imposed by the operational environment. At the HFR two irradiation campaigns have been performed in order to provide the needed design data for some peculiar aspects of the JET.

In the first irradiation campaign, the behaviour of magnet insulation materials (epoxy resins) has been investigated. Representative components of magnet sectors have been irradiated in a specially designed device, shown in **fig. 16**, providing neutron and $\gamma$ spectra tailoring. The mechanism of gas production (mostly $H_2$) due to radiolysis, has been assessed by means of continuous gas release measurements and by post irradiation examinations of samples **(see fig. 17)**.

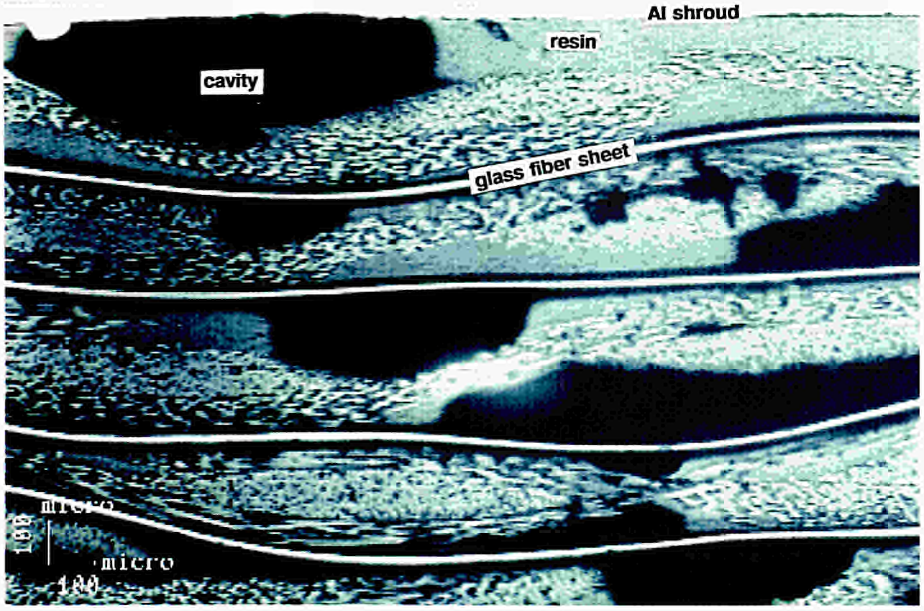


**Fig. 17**
Picture of a sample taken by an optical microscope

**Table 13** presents a summary of the irradiation campaign.

The second irradiation campaign, also ended in 1993, has concerned the irradiation of components of the in vessel inspection system (IVIS) used at JET to ascertain damage at its structures after plasma burning phases. Components of various nature and materials (cameras, glasses, lenses, lamps, cables, motors) have been irradiated and tested according to their operation requirements. Besides the standard recording of temperature and neutron dose, specific in-pile and/or out of pile measurements have been performed according to the component in irradiation (i.e. quality of the pictures for the cameras, torque in case of the motors, etc). **Table 14** contains a summary of the irradiations performed. **Fig. 18** shows radiation effects on a cable (polymer : EPDM) according to IEC544 recommendations /3/. **Fig. 19** shows an example of degradation of a glass (borosilicate ring).

**Table 13**
Irradiation of components

| Experiment | | Material | Total dose (Gy) | Tests |
|---|---|---|---|---|
| Name | Code | | | |
| EPIRO (Epoxy Resins Irradiation) | TP 272-00 | Magnet insulation components (Epoxy resins) | $3 \times 10^5$ | Pressure release radiolysis; mechanical integrity of the resins |
| | TP 272-01 | | $0.8 \times 10^5$ | |
| | TP 272-02 | | $10^6$ | |
| | TP 272-03 | | $10^7$ | |

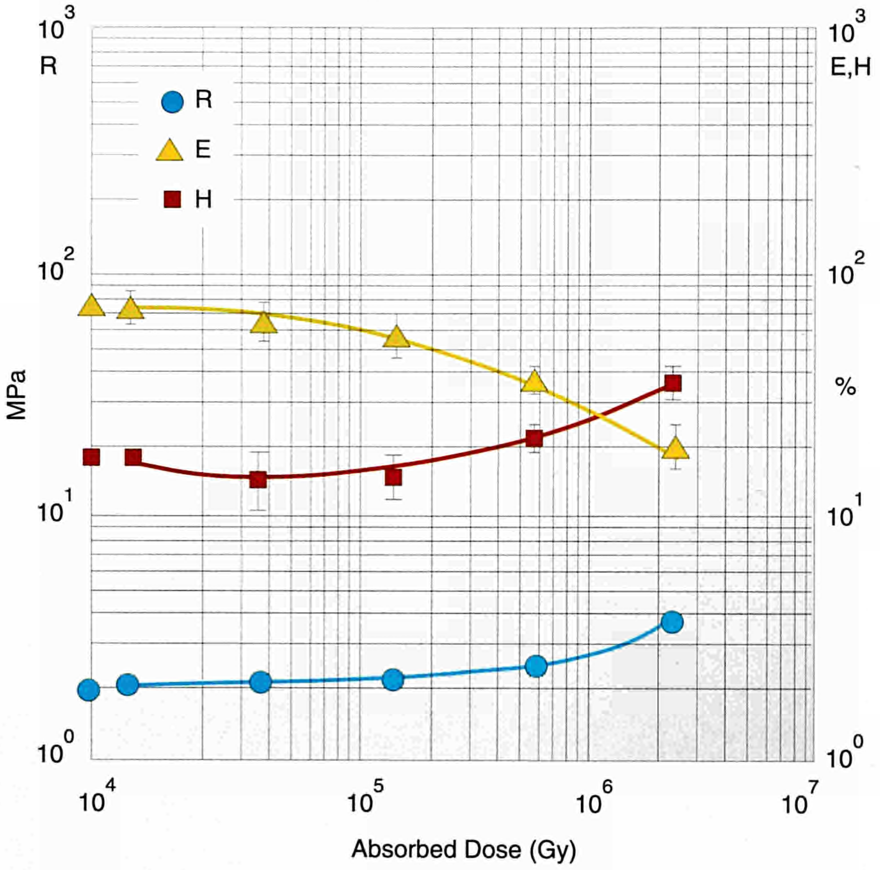
Temperature 350 K
Neutron dose rate (E> 0.1 MeV) $6 \times 10^{15}$ $m^{-2}$ $s^{-1}$

| Component | Neutron dose (E> 0.1 MeV) | Tests performed |
|---|---|---|
| Chalnicon<br>Camera Rees E 93 | $3 \times 10^{17}$ $m^{-2}$ in steps and $8 \times 10^{17}$ | Monitoring, under irradiation, of the picture quality; determination of recovery times; identification of damaged electronic components after failure |
| Vidicon<br>Camera Rees E93 | $1.2 \times 10^{18}$ $m^{-2}$ in steps | |
| Camera<br>Harwell design | $1.2 \times 10^{18}$ $m^{-2}$ in steps | |
| Glasses (borosilicate cylinders, quartz prism, light guide rods, sapphire windows, CaF window, camera lenses | five steps:<br>$3 \times 10^{18}$, $1.2 \times 10^{19}$, $4.8 \times 10^{19}$, $2 \times 10^{20}$, $8 \times 10^{20}$ | Measurements of the reduction of the light transmission as a function of the dose |
| Lamps | five steps:<br>$3 \times 10^{18}$, $1.2 \times 10^{19}$, $4.8 \times 10^{19}$, $2 \times 10^{20}$, $8 \times 10^{20}$ | Measurements of the reduction of the emitted light of the lamps as a function of the dose collected |
| Cables (polymers) | five steps:<br>$3 \times 10^{18}$, $1.2 \times 10^{19}$, $4.8 \times 10^{19}$, $2 \times 10^{20}$, $8 \times 10^{20}$ | Tests as recommended by IEC 544 (tensile properties, hardness, etc.) |
| Motors | five steps:<br>$3 \times 10^{18}$, $1.2 \times 10^{19}$, $4.8 \times 10^{19}$, $2 \times 10^{20}$, $8 \times 10^{20}$ | Determination of radiation resistance of motors, by means of continuous monitoring, during irradiation of the torque motors could deliver; identification of damaged components after irradiation end |

**Table 14**
CARIATIDE experiment

**Fig. 18**
Radiation effects on insulating material

## Determination of Effects of Ionizing Radiation on Insulating Materials, IEC 544

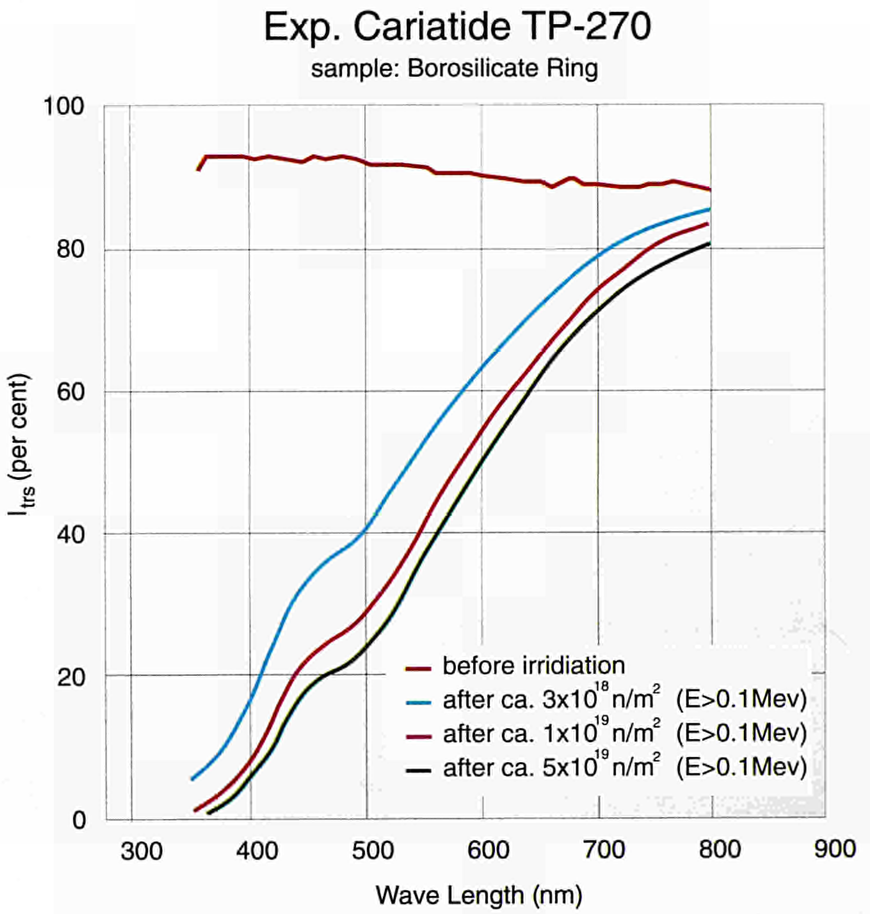


Material : Synthetic Rubber EPDM
Type : 3300/004
Supplier : Meegtechnic
Remarks : taken from sheath

TEST RESULTS:

| Dose (MGy) | Dose rate (Gy/H) | Tensile Properties Strength R (MPa) | Tensile Properties Elongation E (%) | Hardness Shore D H (Degree) |
|---|---|---|---|---|
| 0.000 | - | 2.0 ± 0.1 | 77.5 ± 06.5 | 17.5 ± 2.1 |
| 0.009 | $10^4$ | 2.0 ± 0.1 | 76.3 ± 08.5 | 17.3 ± 1.0 |
| 0.036 | $10^6$ | 2.1 ± 0.1 | 65.6 ± 10.1 | 14.5 ± 4.0 |
| 0.140 | $10^5$ | 2.1 ± 0.1 | 57.0 ± 10.4 | 14.0 ± 3.4 |
| 0.600 | $10^6$ | 2.4 ± 0.0 | 37.5 ± 03.5 | 21.0 ± 0.0 |
| 2.400 | $10^6$ | 3.7 ± 0.2 | 20.0 ± 04.3 | 36.0 ± 5.3 |

**Fig. 19**
Irradiation induced change of the light transmission spectrum of glass materials



## 3.4.4. Blanket Breeder Materials Irradiations

Ceramic lithium compounds and beryllium as neutron multiplier material for BOT (Breeder Outside Tube) and BIT (Breeder Inside Tube) blanket concepts and the eutectic alloy Pb-17Li for the water-cooled liquid blanket concept are being tested for different experimental programmes at the HFR Petten /4/. These experimental programmes, codename EXOTIC, BERYLLIUM and LIBRETTO, are being performed for and in close co-operation with ECN Petten, KfK Karlsruhe, CEA Saclay, CEA Fontenay-aux-Roses, ENEA Casacia, AECL Chalk River and JRC Ispra within the European Fusion Technology Programme on Blanket Breeder Technology.

The main objectives of these experimental programmes are:

(1) Determination of tritium release kinetics by in-situ tritium release measurements in function of temperature, purge gas chemistry, tritium production rate and lithium-burn-up from materials of different fabrication routes.
(2) investigation of irradiation damage by fast neutron irradiation and high lithium-burn-up.
(3) Compatibility between structural and breeder materials.

(4) In-situ examination of tritium permeation through cladding materials, and the effectiveness of permeation barriers.
(5) In-situ study of tritium extraction methods.
(6) Tritium inventory, swelling and embrittlement of beryllium.

The results of the Petten experiments have a prominent share in the selection procedures of blanket concepts and their breeder materials for ITER and DEMO. The selection will start before the end of the current 1992-1994 European Fusion Technology Programme. This means that discussions on future blanket related irradiation programmes will start soon, and will most likely be focused on long-term integrated tests of blanket modules. Preparatory feasibility studies at IAM Petten were already initiated. They revealed that the HFR with its wide range of nuclear characteristics, the available facilities, the long-standing experience and knowledge on irradiation technology for blanket materials, is very well qualified for the challenge of forthcoming integrated tests on blanket modules.

An overview on the current irradiation programmes at the HFR is given in **table 15**.

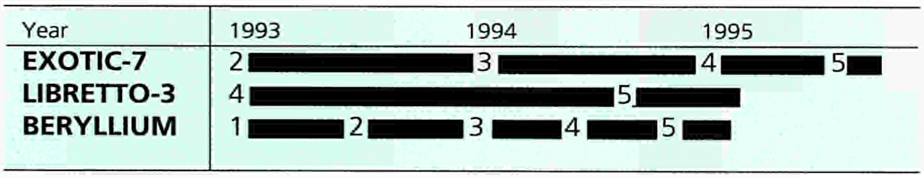


**Table 15**
Fusion blanket breeder experiments. Survey of present and future activities
**Legend:**
1 Design & calculation
2 Manufacture and commissioning
3 Irradiation
4 Dismantling & PIE
5 Final report

EXOTIC, Irradiation of ceramic lithium compounds and beryllium

The experimental programme EXOTIC is being carried out at the HFR Petten since 1984. It comprises manufacture, characterization, irradiation and pre- and post-irradiation examination of the lithium compounds $LiAlO_2$, $Li_2SiO_3$, $Li_4SiO_4$, $Li_2O$, $Li_2ZrO_3$, $Li_6Zr_2O_7$ and $Li_8ZrO_6$, and of beryllium. ECN Petten coordinates the EXOTIC programme and performs the major part of post-irradiation examinations. The EXOTIC project is carried out with strong international participation. NRL Springsfield and SCK/CEN Mol, as well JAERI and ANL participated in the first four EXOTIC experiments. CEA Saclay, KfK Karlsruhe, ENEA Casaccia and AECL participate in the EXOTIC-5,-6 and -7 irradiation tests.

The programme on blanket materials within the European Fusion Technology Programme was reoriented in 1988. Three categories of irradiation experiments were defined, namely short-, medium- and long-term irradiations. One important goal was that all candidate ceramic tritium breeding materials should be tested in these tests. The 'medium-term' experiments, EXOTIC-5 and EXOTIC-6, were performed at the HFR Petten between 1989 and 1992 up to lithium-burn-ups of 3% /2,9/. In-situ tritium release measurements were performed by means of specially developed facilities, comprising twelve tritium measuring trains. Tritium release data were obtained from sixteen different materials in dependence of temperature, purge gas chemistry, tritium production rate and lithium-burn-up. These in-reactor data were evaluated by IAM Petten and ECN

Petten, and were, together with first post-irradiation examinations, published at recent SOFT and ICFRM conferences /10,11/. Post-irradiation examinations of EXOTIC-6 will be terminated in 1994.

The European reference long-term irradiation experiment on materials for solid blankets was originally planned to be performed in 'PHENIX', which provides a more fusion like neutron spectrum. But, due to uncertainties in the operation licence, it was agreed between the partners to perform the test at the HFR Petten. Feasibility studies demonstrated that the required lithium-burn-up of ±10 % could be achieved with a one year irradiation at the HFR.

Design work for EXOTIC-7 started in 1992. Eight different ceramic lithium compounds, partially mixed with beryllium, will be irradiated in eight purged capsules, each provided with operational features as in-situ tritium release measurements and individual temperature control /2,4/. The objective of EXOTIC-7 is the investigation of the behaviour of lithium based breeder materials and beryllium with respect to tritium release, tritium inventory and pellet / pebble mechanical integrity at high lithium-burn-up and high fast neutron fluence.

In 1993, manufacture and assembly progressed as planned. Irradiation is planned for a period of 11 cycles, to be started early in 1994.

### BERYLLIUM, Irradiation of neutron multiplier material beryllium

The objective of the Beryllium experiment, a KfK Karlsruhe sponsored project to be performed at the HFR Petten, is to investigate the tritium inventory, swelling and embrittlement of beryllium pebbles, and the recoil of tritium from $Li_4SiO_4$ pebbles into adjacent beryllium pebbles. The work contributes to the fusion programme of KfK Karlsruhe for the development of a helium-cooled BOT (Breeder-Out-of-Tube) ceramic blanket for DEMO. The target material will be tested in eight closed capsules, whereby a required test matrix with three temperature levels, 673 / 773/ 823K, and two neutron fluence levels, 0.5 and 1.5 $10^{25}$ $m^{-2}$ (>1 MeV), can be achieved.

The design and manufacture of the irradiation facility was performed in 1993. Irradiation is planned to start early in 1994 for a period of four HFR cycles in a central in-core position.

### LIBRETTO, Irradiation of the liquid blanket breeder material, Pb-17Li

The experimental programme LIBRETTO is being carried out since 1987 as a joint programme between JRC Ispra, CEA Fontenay-aux-Roses and CEA Saclay, in co-operation with IAM Petten. The objectives of the LIBRETTO experiments are the in-pile testing of the eutectic alloy Pb-17Li in a mixed neutron spectrum with the aim to assess tritium release kinetics, tritium extraction methods, compatibility studies, tritium permeation and the effectiveness of tritium permeation barriers. Tritium release is being measured in-situ and on-line with specially developed tritium measuring trains. The results of the LIBRETTO experiments are of prominent importance for the design of water-cooled and self-cooled liquid blanket concepts for DEMO.

Three successful LIBRETTO irradiation campaigns were conducted at the HFR Petten. The work for the first two LIBRETTO experiments has been brought to an end in 1992 /2/. The LIBRETTO-3 irradiation was performed in 1992 at the HFR during 77 full power days to compare the efficiency of three different tritium permeation barriers in the presence of Pb-17Li to uncoated AISI 316L steel /2,12/. For this purpose four steel capsules were filled with 28 g Pb-17Li. The coatings included CVD TiC (outside), CVD TiC+$Al_2O_3$ (inside), and pack cementation aluminisation (inside). The generated tritium was partly extracted by bubbling, partly it permeated through the capsules. Permeated and extracted tritium were measured as a function of temperature (553-723K), $H_2$ doping (0-1 vol %) and purge gas flow rate (0-100 $cm^3$/min). The driving partial pressure in the coated capsules was tentatively evaluated from an extraction model calibrated by the uncoated capsule for which tritium partial pressure could be calculated. In LIBRETTO-3, the best barrier was pack cementation aluminisation with a permeation reduction factor of 15.

Work in 1993 has concentrated on dismantling and post-irradiation examinations. After a neutronradiography was taken, the sample holders were dismantled at the ECN hot cells and the four capsules with the eutectic alloy (Pb-17Li) were recovered and prepared for transport to JRC Ispra, where detailed post-irradiations examinations will be performed.

A continuation of LIBRETTO type irradiations at the HFR Petten is depending upon the forthcoming selection of (a) blanket concept(s) for ITER / DEMO within the next European Fusion Technology Programme (1995 - 1998).

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## 3.5. RADIOISOTOPES PRODUCTION

Radioisotopes produced in research reactors play an increasingly important role in nuclear medicine aside of their confirmed application in science and technology. More than 7 million treatments per year are performed in the nuclear medical departments of hospitals within the European Union.
The HFR is presently the largest supplier of radioisotopes in Europe.

The radioisotopes production is still growing at the HFR. The amount of work performed in 1993 was again larger than in the previous year. **Fig. 20** shows, in relative values, the production in the last five years.
The regular operation of the HFR, the quality of the service offered, the quick reactions to clients requests are the strong points which have allowed the growth of this activity.

Presently the radioisotopes production represents the main third party source of income in the IAM. Moreover, this activity is vital for millions of patients treated with radio-pharmaceuticals either for diagnostic or for therapeutic purposes.

A radio-pharmaceutical consists of an appropriate stable chemical labelled with a certain amount of the corresponding radioisotope. Radioisotopes for medical use represent more than 85% of the total production at the HFR. The remaining part concerns production for industrial or scientific applications /1,2,3/. Taking into account the reduction of the number of reactors in operation, the HFR can be considered as the key reactor in Europe for this kind of production.

**Table 16** contains a list of the most important radioisotopes produced for medical applications at the HFR.

An average of 130 capsules per reactor cycle has been irradiated in the standard radioisotopes devices; characteristics of the facilities are summarized in **tables 17 and 18. Fig. 21** shows the FACHIRO device, with a view of a typical loading of Ir discs. **Fig. 22** shows the RODEO device. A detail of an irradiation capsule containing iridium wires is also shown.

Fissile targets for the production of $^{99}$ Mo, from which $^{99m}$Tc is generated (the most powerful diagnostic tool in nuclear medicine) are being routinely irradiated in new designed devices **(see fig. 23)**. These devices, called PROMETEO allow independent irradiation of two batches of three tubular targets each, at a fluence rate $\Phi_{th}$= 1.2x10$^{18}$m–$^{2}$s–$^{1}$. The devices can be installed in any PSF rail and can be operated at any time.

Moreover, other devices for irradiation of fuel plates are being designed. The project named MYKONOS foresees irradiation of four batches of two fuel plates, each in one single device. Irradiation characteristics are similar to those related to fuel tubes irradiations.

The radioisotopes production is performed following the flow schemes shown in **figs. 24 and 25**. Each step of the procedure is carefully performed and checked according to a strict quality assurance procedure /4/ to guarantee, at any moment, a safe and reliable service from the preparation of the irradiation capsules up to the transport of the containers.

**Fig. 20**
Radioisotopes productions in the last five years; relative values

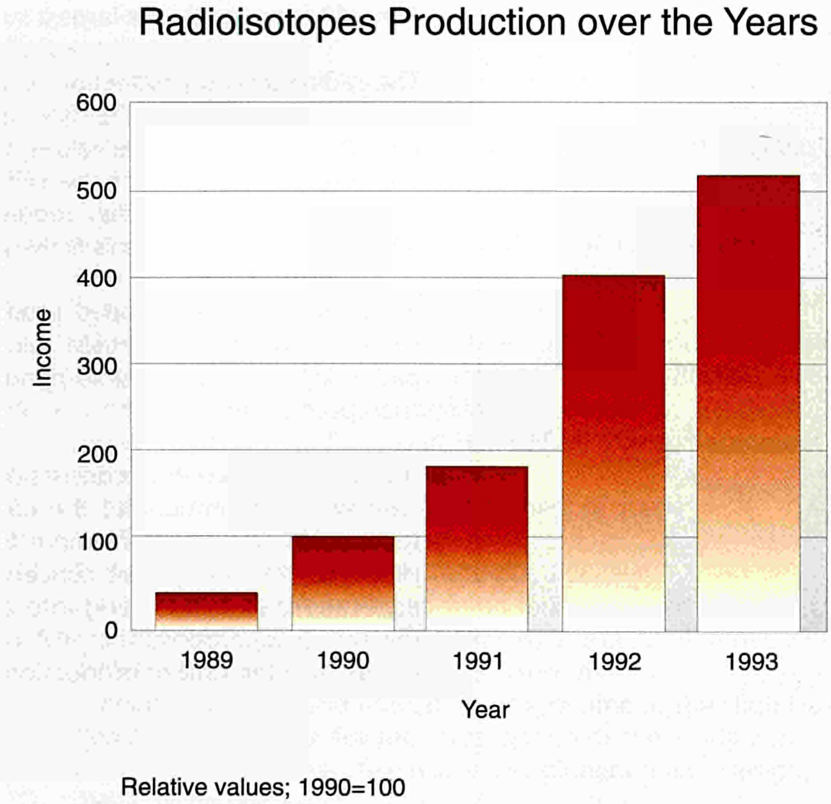

**Fig. 26** shows the reactor hall crowded with containers ready for transport.
In 1993 more than 800 transports have been organised.

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Quality Assurance Procedure for the HFR Radioisotopes
EUR report, 1994, to be published

**Table 16**
Most important radioisotopes produced for medical applications at HFR

| | |
|---|---|
| Technetium ($^{99m}$Tc) | Bone imaging agent to delineate areas of altered osteogenesis; general use for tumour scintigraphy; brain and renal perfusion imaging; liver, spleen, medullary, lung imaging; visualization of airways potency; labelling of red blood cells, visualization of blood pools (hearth, placenta); intestine imaging |
| Iridium ($^{192}$Ir) | Destruction of malignant tumours by interstitial or intracavitary radiotherapy, using needles or wires and treatment of superficial cancers;<br>used as collimator in gynaecology, urology, surgery, pulmonology etc. |
| Yttrium ($^{90}$Y) | Treatment of liver cancer; pain killer of metastatic bone cancer |
| Strontium ($^{89}$Sr) | Pain palliation in prostatic skeletal malignancy |
| Iodine ($^{125}$I) | Investigation of thyroid |
| Phosphorus ($^{32}$P) | Treatment of skin angiomas |

| Facility | Description | Quantity |
|---|---|---|
| FACHIRO (core) | By fluence rate trap technique, using a maximum of moderator (water) and a minimum of structural material (Al) a high thermal flux is achieved. Up to 25 capsules can be located in the device. Facility cannot be accessed during reactor operation.<br>Very suitable for iridium (discs, pellets) production. | 8 |
| RIF (core) | Facility is a simple holder placed in a thimble. High fast flux is reached. Up to 20 capsules can be irradiated at the same time. Facility can be accessed during reactor operation.<br>Suitable for iodine production. | 1 |
| FARO (core) | Reloadable device, designed for $^{32}P$ production. | 1 |
| TIRO (core) | Reloadable device, making use of fluence rate trap technique. | 1 |
| HFPIF (PSF) | Facility, which can be installed on any rail of the PSF table consists of two tubes arranged behind each other. Ten capsules can be irradiated at the same time. A Cd shielding can be provided. The facility can be accessed during reactor operation. Suitable for iridium wires. | 2 |
| HIP (PSF) | Facility similar to HFPIF, but more flexible. It allows simultaneous irradiation of 30 capsules with three different diameters. | 2 |
| RODEO | Rotating device designed for the irradiation of iridium wires and needles. The facility will be placed in the I row (reflector elements) of the reactor. Five capsules can be simultaneously irradiated. Uniform fluence rate distribution is assured by the rotation. | 1 |
| PRS and FASY | Two conveyor systems are available and are automatically operated. They are used for activation analysis purposes. Irradiations are performed in polyethene shuttles.<br>Pneumatic systems send the capsule to the counting positions, if required. | 2 |
| PROF | Rotating facility for irradiation of big samples (diameter about 50 mm) in a polyethene sample holder. Low fluence rate ($\Phi_{th} = 4 \times 10^{12}$ cm $^{-2}$ s $^{-1}$). Used for activation of biological samples. | |

**Table 17**
Radioisotopes facilities

| Facility | Inside (mm) | | Outside (mm) | | Irradiation (time) | Thermal Flux ($10^{14}$ cm$^{-2}$ s$^{-1}$) | Fast Flux (E> 0.1 MeV) ($10^{14}$ cm$^{-2}$ s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| | diameter | length | diameter | length | | | |
| FACHIRO | 14 or 9 | 70 | 15 or 10 | 80 | 25 days or multiple | 4.5 | 1.7 |
| RIF | 14 or 9 | 45 | 15 or 10 | 50 | as wished | 2.1 | 1.7 |
| FARO | 23 | 70 | 25 | 80 | as wished | 2.1 | 1.7 |
| TIRO | 9, 14, 23 | 70 | 10, 15, 25 | 80 | as wished | 2.4 | 1.6 |
| HFPIF | 23 | 70 | 25 | 80 | as wished | 2.5 | 0.35 |
| HIP | 9, 14, 23 | 70 | 10, 15, 25 | 80 | as wished | 2.5 | 0.35 |
| RODEO | 23 | 70 | 25 | 80 | as wished | 0.626 | 0.098 |
| PRS | 15 | 70 | 22 | 100 | maximum 1 hour | 0.4 | 0.023 |
| FASY I, II | 10 | 19 | 12 | 20 | 15 minutes | 0.814 0.013 | 0.054 0.002 |
| PROF | 55 | 120 | 50 | 110 | maximum 24 hours | 0.04 | 0.005 |

Irradiation of capsules of different dimensions is possible, on request.

**Table 18**
Flux values (unpertubed values) and dimensions of capsules

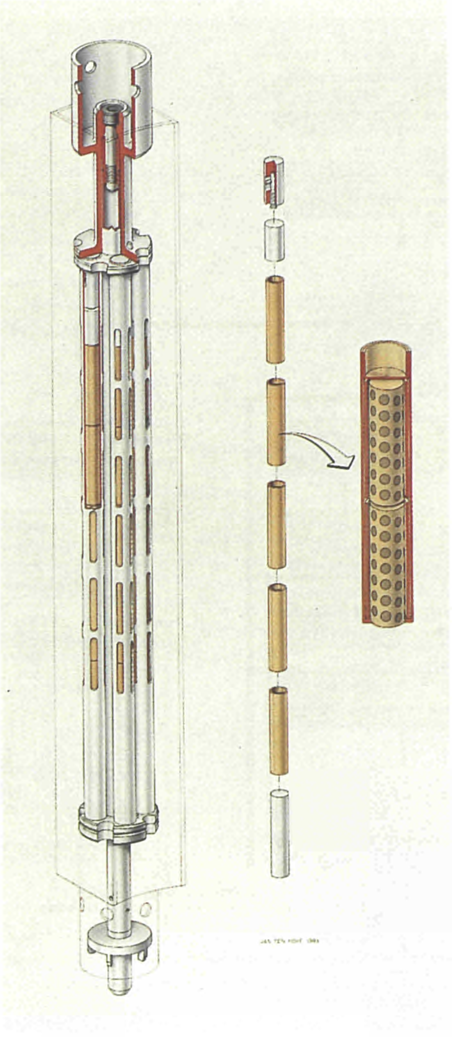


Fig. 21
FACHIRO rig

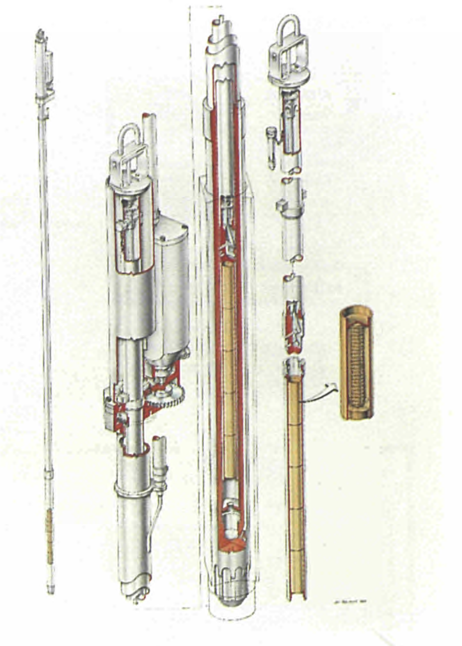


Fig. 22
RODEO device

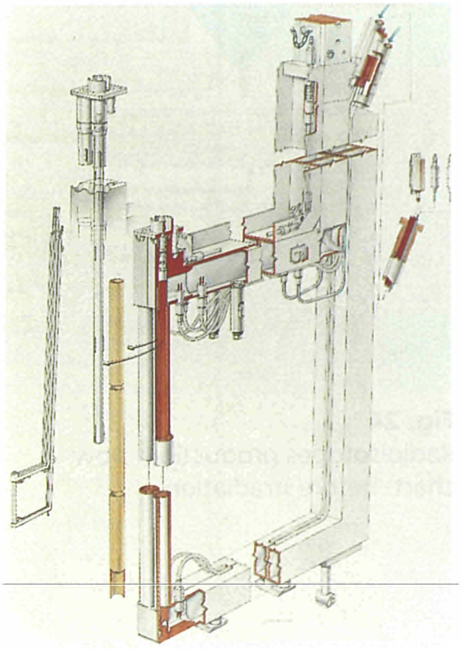
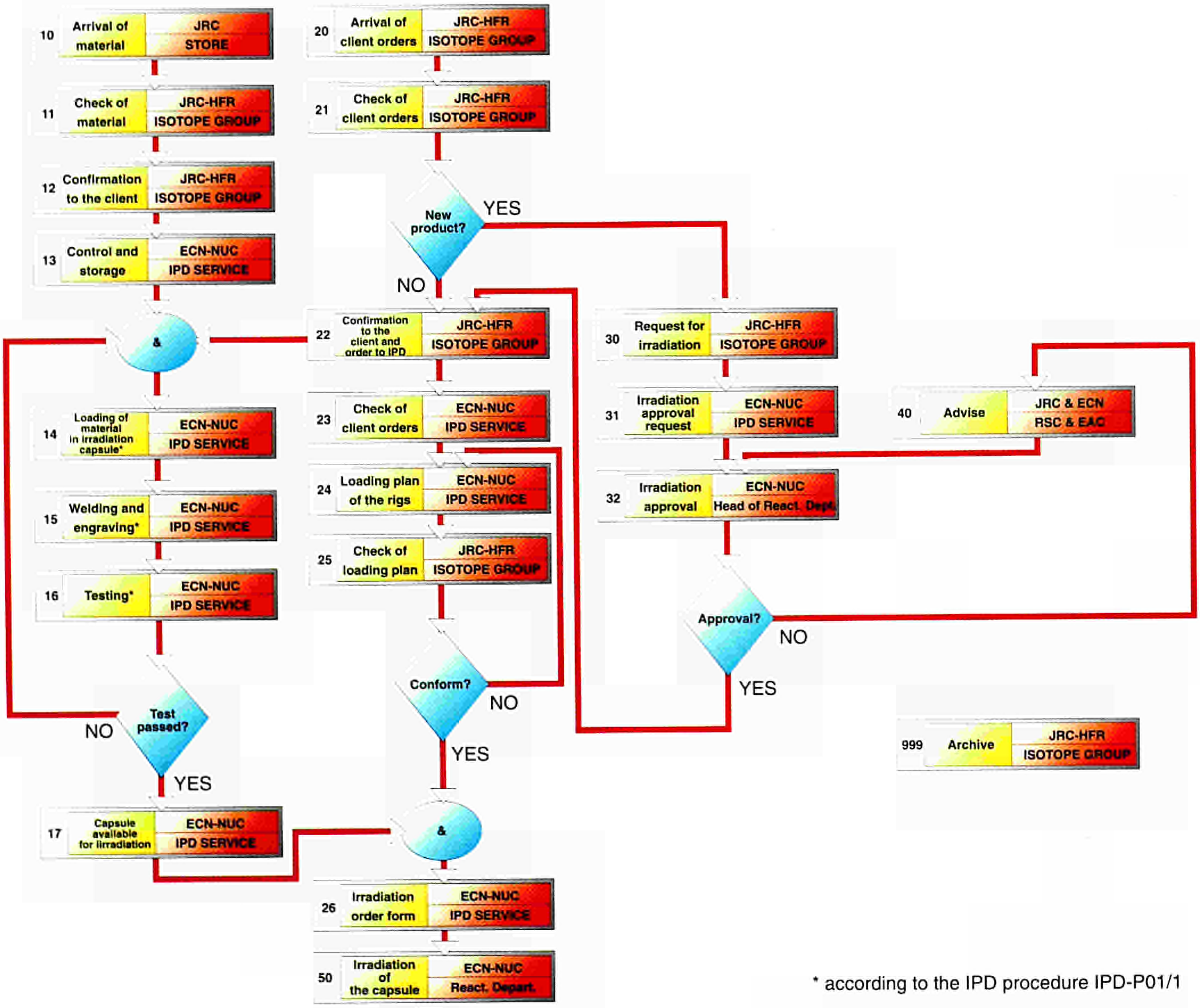


Fig. 23
PROMETEO device



* according to the IPD procedure IPD-P01/1

**Fig. 24**
Radioisotopes production, flow chart: before irradiation

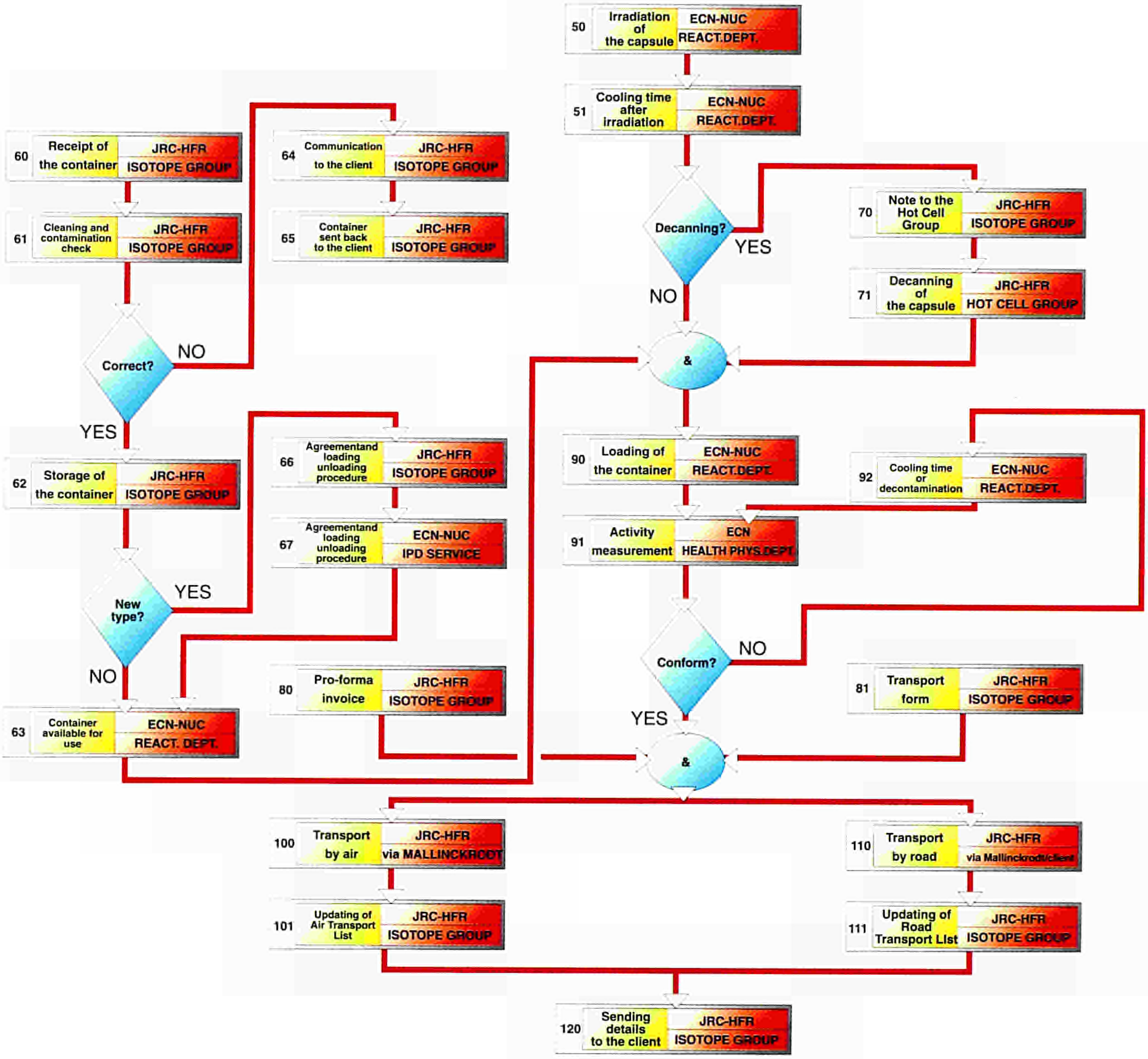


**Fig. 25**
Radioisotopes production, flow chart: after irradiation

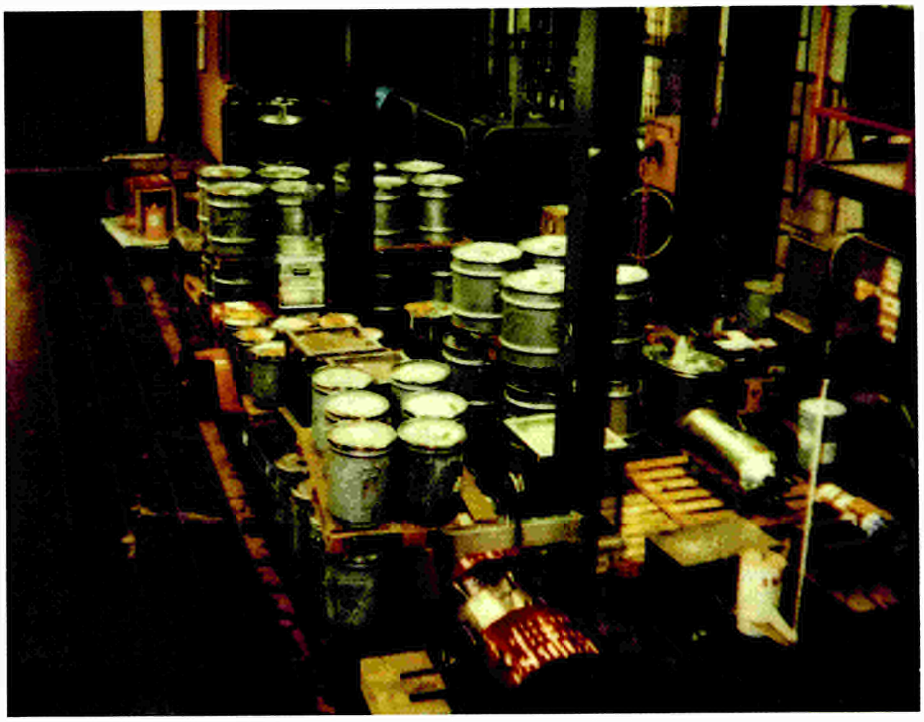


**Fig. 26**
Radioisotopes containers in reactor hall

## 3.6. ACTIVATION ANALYSIS

Devices used for general radioisotopes production are also used to irradiate various kinds of materials for scientific applications. Comprehensive equipment for post irradiation counting is available at the Petten premises (ECN).

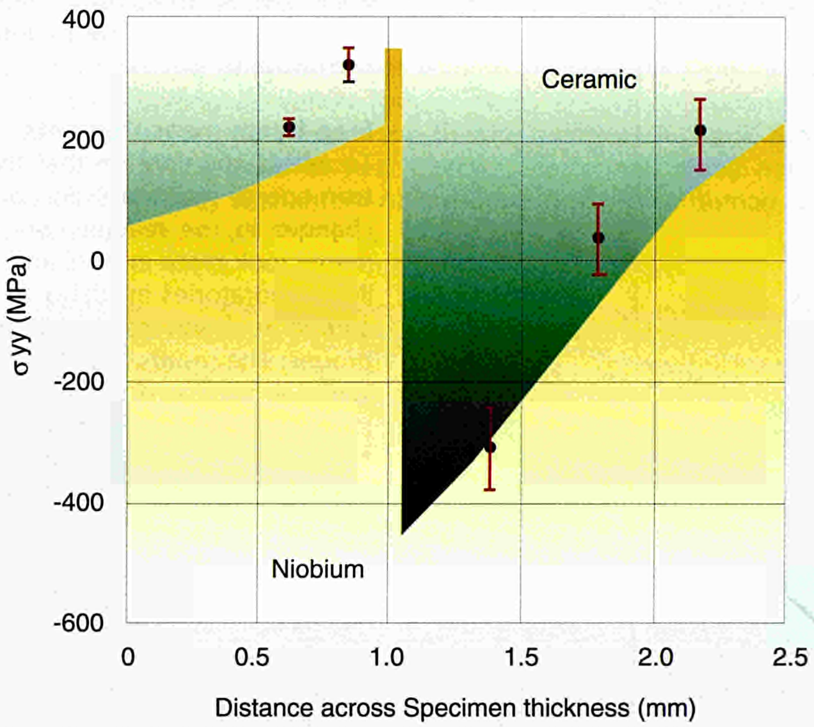
Activation analysis is used in the archaeologic field, in geology (rare earth, sedimentary studies), in forensic applications and in environmental studies (atmosphere particles, aerosols, toxicology). In 1993 irradiations for British, German and Dutch Universities continued (age determination of rocks, mineral composition etc.).

## 3.7. SOLID STATE PHYSICS AND MATERIALS SCIENCE

At the beginning of 1993 the group Characterization of the Service Unit ECN-Technology operated six neutron-scattering instruments installed at five of the horizontal beam tubes. The research subjects were in the fields Solid State Physics, Physical Chemistry and Materials Science. After the first quarter a PhD project in Colloid Chemistry was discontinued, and as a consequence the small-angle scattering instrument was taken out of operation.

The diffraction instrument HB4 was dedicated to a joint IAM/JRC exploratory project, aimed at investigating the feasibility of neutron diffraction for the non-destructive measurement of residual stresses in materials, in particular near interfaces. Measurements of stress gradients near the surface of shot peened steels and near the interface of the bond layer in steel-silicon nitride joints yield realistic levels of the stresses and acceptable error margins, provided that the sampling volume and the path length of the neutron beam through the ceramic are optimized towards maximizing the ratio of the amplitude of the diffracted beam over the background noise.

**Fig. 27**
Computed (solid line) and measured, by neutron scattering, residual stresses parallel to the bonded interface in a Hot Pressed Silicon Nitride/Niobium joint specimen



Investigation of crystallographic and magnetic structures by neutron diffraction forms part of a long-term co-operation with the University at Leiden and the Technical University at Eindhoven. Two joint PhD research projects are aimed at intermetallic uranium compounds and diluted magnetic semiconductors, respectively. The latter project was completed successfully. In addition to the long-term research, a number of diffraction patterns for polycrystalline samples were recorded upon request of the Gorlaeus Laboratories, Leiden.

## 3.8. BORON NEUTRON CAPTURE THERAPY (BNCT)

The development of Boron Neutron Capture Therapy (BNCT) as a treatment modality for curing tumours, especially glioma, continues steadily on its course towards the initiation of the first European clinical trials within the next year. BNCT utilises the energy produced by the instantaneous nuclear fission of a boron-10 nucleus into an alpha particle and a lithium ion, after the capture of a slow (thermal) neutron, i.e. $^{10}B(n,\alpha)^{7}Li$. The emitted irradiation destroys those cells in which the boron capture event takes place. Hence, providing there is a sufficient amount of $^{10}B$ nuclei in the cancerous cells, and a sufficient differential between the $^{10}B$ nuclei in the cancerous cells and healthy cells, then the tumour can be destroyed without causing damage to the healthy tissue. To achieve this, one needs a suitable, preferentially tumour-seeking boron compound and a high flux of thermal neutrons at the tumour site. With respect to the latter, the beam tube HB11 produces an epithermal neutron beam with the appropriate characteristics. In recent years, as reported on previous occasions an extensive programme of work has been in progress, including: regular free beam characterization; healthy tissue tolerance studies; cell culture experiments; treatment planning development, including in-phantom measurements; on-line monitoring; and the design of the clinical treatment room.

**Free-beam measurements**

To assess and confirm that the beam parameters (flux intensity and neutron energy spectrum) do not change or are not significantly affected by changes in the reactor core configuration, further free-beam measurements took place in April and June. For the second time, a group from the INEL laboratories in Idaho took measurements also, as part of an intercomparison and collaboration exercise between the US and European groups. The results of these latest measurements, being the sixth in recent years, show that the beam is very stable. The most recent measurements indicate that the beam parameters vary by no more than 1-2%, see **table 19**. The latest measurements and calculations confirm the HB11 characteristics, indicated in **table 20**.

| | ratio : - reaction rate : reference reaction rate (03.04.92) | | | | | |
|---|---|---|---|---|---|---|
| foil and reaction | 03.07.91 | 03.04.92 | 21.05.92 | 10.07.92 | 27.10.92 | 11.06.93 |
| $^{197}$Au(n,$\gamma$) | 1.04 | 1.00 | 0.95 | 0.95 | 0.95 | 0.95 |
| $^{115}$In(n,$\gamma$) + Cd | 0.96 | 1.00 | 0.94 | 0.94 | 0.98 | 0.99 |
| $^{45}$Sc(n,$\gamma$) + Cd | 0.99 | 1.00 | 0.95 | 0.97 | 0.94 | 0.97 |
| $^{197}$Au(n,$\gamma$) + Cd | 1.01 | 1.00 | 0.95 | 0.96 | 0.94 | 0.96 |
| $^{186}$W(n,$\gamma$) + Cd | 0.96 | 1.00 | 0.94 | 0.95 | 0.95 | 0.95 |
| $^{238}$U(n,$\gamma$) + Cd | 0.98 | 1.00 | 0.95 | 0.95 | 0.94 | 0.94 |
| $^{139}$La(n,$\gamma$) + Cd | 0.98 | 1.00 | 0.95 | 0.96 | 0.94 | 0.95 |
| $^{55}$Mn(n,$\gamma$) + Cd | 1.00 | 1.00 | 0.92 | 0.96 | 0.95 | 0.94 |
| $^{63}$Cu(n,$\gamma$) + Cd | 1.01 | 1.00 | 0.94 | 0.95 | 0.94 | 0.95 |
| $^{115}$In(n,n) + Cd | 1.22 | 1.00 | 0.87 | 0.92 | 0.93 | 0.99 |
| $^{58}$Ni(n,p) + Cd | 2.63 | 1.00 | 0.93 | 0.94 | 1.03 | 0.92 |
| $^{27}$Al(n,$\alpha$) + Cd | – | 1.00 | 0.88 | 1.03 | 0.95 | 0.93 |

**Table 19**

Comparison of free beam measurements at the HB11/BNCT facility

### Phantom measurements

Numerous phantom irradiations were performed and repeated from the previous year. The measurements determine the thermal neutron flux distribution within the body or target volume. Tissue-equivalent or plastic phantoms containing activation foils or wires and thermoluminescence detectors (TLDs) are irradiated at the therapy position. In April, a group from the Nuclear Institute at Rez, Czechia, performed some measurements at HB11 using a phantom of the upper torso of a human, which included internally, a real skeleton.

**Table 20**
Nuclear characteristics of the HB11/BNCT epithermal neutron beam

| | |
|---|---|
| Total neutron flux | $3.8 \times 10^{8}$ n/cm$^2$/s |
| Thermal neutron flux (< 0.414 eV) | $2.6 \times 10^{6}$ n/cm$^2$/s |
| Epithermal neutron flux (0.414 eV to 10 keV) | $3.3 \times 10^{8}$ n/cm$^2$/s |
| Fast neutron flux (> 10 keV) | $4.9 \times 10^{7}$ n/cm$^2$/s * |
| Ratio of fast to epithermal flux | 0.15 |
| Ratio of fast total flux | 0.13 |
| "Average" neutron energy | 10.4 keV |
| Incident gamma dose (fresh argon) | 1.00 Gy/h * |
| Incident gamma dose (activated argon) | 1.25 Gy/h * |
| Fast neutron dose | 1.04 Gy/h * |
| Fast neutron dose per epithermal neutron | $8.6 \times 10^{-13}$ Gy-cm$^2$ * |
| Gamma dose per epithermal neutron | $10.34 \times 10^{-13}$ Gy-cm$^2$ * |

* = measured values

### Cell culture irradiation experiments

Further irradiations were performed to observe the effect of the boron capture reaction at depth inside a phantom and to determine the RBE values of the various beam components. Participating groups included JRC and ECN Petten, University of Bremen, FRG, and the Netherlands Cancer Institute in Amsterdam.

### Healthy tissue tolerance studies

The most critical component in the BNCT project is knowledge of the safe dose to be given to the healthy tissue (skin, brain and bone marrow) as a function of boron dose and irradiation time. Consequently, over the last 3 years, a healthy tissue tolerance study has been in progress where 47 canine experiments have been performed. The last irradiation took place in June 1993. By the end of the year, the full range of radiation effects has been observed, including: severe neurological changes, varying between 5-10 months post-irradiation; and, by means of magnetic resonance imaging, limited or no radiation damage at all. This infers that the experiment was accurately performed whilst performing only a limited number of irradiations. There still has to follow at least another 4-6 months observation of the remainder. By then, the healthy tissue tolerance dose for 2 levels of boron concentration should be predictable. In other words, this part of the whole project has been a success and will be concluded, with respect to predicting the starting dose for patient treatment, early next year. The remaining histology work, which affects conclusive evidence only, will be completed during the year.

## On-line dosimetry

The on-line monitoring system, a twinned system of 2 GM tubes and 2 fission chambers, installed behind the gamma shutter in the beam port have been extensively tested. Parameters studied include: effect of reactor core and cycle changes such as the variation from one reactor cycle to another, the variation within a cycle and the influence of the reactor power level eg. during the reactor start-up; effect of the status of the beam shutters and liquid argon filter, such as the individual or combined open or closed status of the various shutters and fresh or activated argon; and effect of backscatter from the patient or phantom. Measurements completed in the first half of the year obtained the following results: reactor power changes of 0.5% can be detected; changes in the neutron: gamma ratio of less than 2% are detectable; the activation of the argon filter increases the gamma signal by 0.3%, the activation of the GM counters themselves contributes another 3%; the external gamma shutter increases the $^{235}$U fission count rate by 2.8%; scattered neutrons from the patient (phantom) increases the $^{235}$U fission count rate by 1.2%. The system has been further improved by positioning 2 more monitors further into the beam tube in order to avoid effects from back-scatter from the patient. This work is primarily conducted by physicists from the Netherlands Cancer Institute, who will need to carry out such tests on an almost daily basis once regular patient treatment starts.

## Treatment planning

To determine the radiation dose distribution in the human head during irradiation treatment, a treatment planning scheme is being developed based on the Monte Carlo code MCNP. The code requires many improvements still, including pre- and post graphical routines and substantial changes to improve calculational time. In this respect, a strong collaborative effort between JRC, the Netherlands Cancer Institute and INEL in Idaho is being built-on.

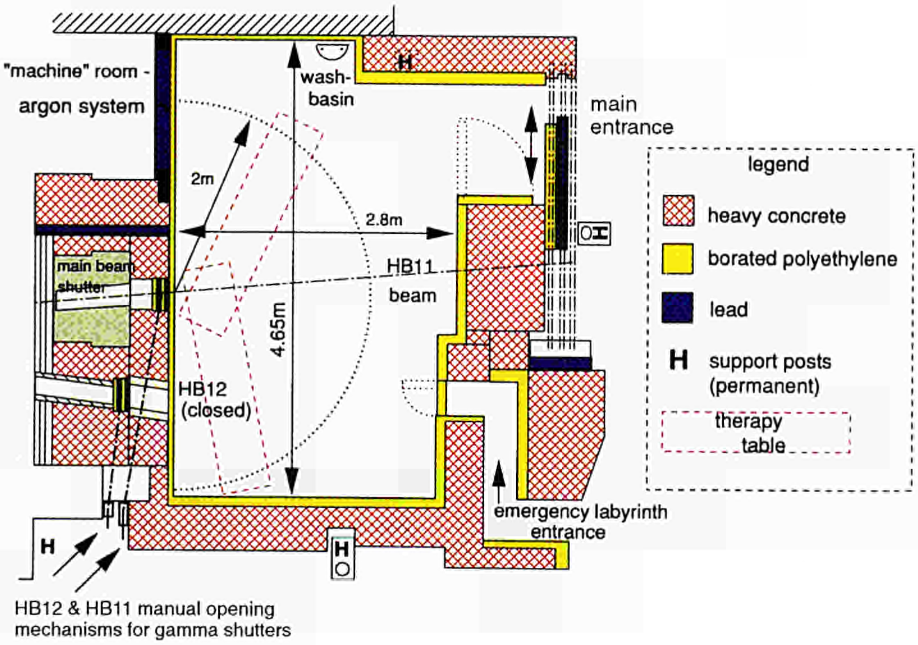


**Fig. 28**
Cross-section through the new, enlarged irradiation room at the HFR BNCT facility

## Patient treatment room

Following the completion of the last irradiation in June of the healthy tissue tolerance study, action was taken immediately to dismantle the small irradiation room and start construction on the new, enlarged room. The irradiation room or treatment area has been enlarged from its old 1.0 $m^2$ set-up to a substantially larger set-up with dimensions 4.65 x 2.8 x. 2.2 $m^3$, **see fig. 28**. The room itself comprises of over 70 tonnes of shielding material. The ceiling consists of 2 layers of solid steel beams, each 100 mm tick, 1 layer of lead bricks, 50 mm thick and 2 layers of borated polyethylene, each 50 mm thick. The inside surfaces of the whole room will be lined with 1 or 2 layers of borated polyethylene plates. The new set-up makes it relatively easy for the positioning and irradiation of patients from any angle. During the coming year, a medical observation area will be created, such that the beam operator or hospital personnel can follow the patient irradiation, eg. irradiation time and dose received by the patient, via an observation console. This will also include an audio/visual unit and emergency control switches. The fully working facility should be ready towards the latter half of the year.

The BNCT project at Petten is entering its final stage, prior to the implementation of clinical trials. During 1994, the patient treatment room will be ready to receive patients. It is expected that clinical trials will begin soon thereafter.

## References

/1/ D. Gabel, R.L. Moss (editors)
Boron Neutron Capture Therapy: Toward Clinical Trials of Glioma Treatment, Plenum Press NY, 1992

/2/ M.W. Konijnenberg, C.P.J. Raaijmakers, L. Dewit, B.J. Mijnheer, R.L. Moss, F. Stecher-Rasmussen, P.R.D. Watkins
Treatment Planning of Boron Neutron Capture Therapy: Measurements and Calculations, Radiation Protection Dosimetry, Vol. 44, no. 1/4, 443-446 (1992), Nuclear Technology Publishing

/3/ M.W. Konijnenberg, B.J. Mijnheer, C.P.J. Raaijmakers, F. Stecher-Rasmussen, P.R.D. Watkins
An Investigation of the Possibilities of BNCT Treatment Planning with the Monte Carlo Method, Stahlentherapie und Onkologie, 169, (1993) 25-28, Nr. 1

## 3.9. NEUTRON RADIOGRAPHY

Neutron radiography is a non-destructive inspection and testing technique capable of producing images of components, assemblies and materials, on film or real time devices. In comparison to X- and gamma- rays, neutrons penetrate heavy metals like steel, lead and uranium much more easily, whilst at the same time having the unique capability to image light materials such as hydrogen bearing materials.

At the HFR, two neutron radiography facilities and an image analysis system are available. The neutron radiography facilities consist of:

- An underwater camera and
- A beam tube-based neutron radiography system at the HB8 beam tube with filtered neutrons and with a real time imaging system.

Neutron radiography services are provided for HFR irradiation projects and for non-nuclear R&D as well as for routine inspections of EC research and industry /1/.

### The HB8 beam tube NR facility

Results of a study on the application of neutron radiography to space technology components were published within the ESA/ESTEC journal /2/. The study was pursued with image taking with non-film-based techniques and image analysis of selected test items using a reactor-based neutron source (HFR) and a neutron tube (GENIE 46) at IABG, Munich. For imaging of small components with the HFR TV-based imaging system, a zooming system was integrated into the existent system and optimized with regard to image quality. It is anticipated to conclude this project during the first quarter of 1994.

The IKE Stuttgart neutron radiography-based tomography system was tested at the HFR using the thermal and the subthermal HB8 beams. The objective was to investigate the system performance with approx. 10 times higher neutron fluence rates as experienced sofar and for the first time with subthermal neutrons. After full evaluation of the results of the investigation another measuring campaign will follow in 1994.

Neutron radiography inspections were performed as a service to industry and research. These inspections related to checks of mechanical devices from launchers of space craft and satellites.

### The HFR underwater NR camera

Routine neutron radiographic inspections as a service to irradiation experiments have been performed following the requirements of the various HFR irradiation programmes.

### Neutron Radiography Working Group (NRWG)

The NRWG, on its 1993 June meeting in Portoroz/Slovenia, reorganized itself, decided to enlarge the Working Group membership to neutron radiographers and organizations from all European countries and to rename the Working Group. Its name is now European Neutron

Radiography Working Group (ENRWG). The ENRWG will continue the activities of the former NRWG.

Assistance has been provided within the WCNR (World Conference on Neutron Radiography) Series Coordination Committee.
The Fifth World Conference on Neutron Radiography will be held in June 1995 in Berlin, organized and hosted by the German Society for Non-Destructive Testing (DGZfP).

**References**

/1/ J.F.W. Markgraf (editor)
Neutron radiography at the HFR Petten Compilation of the HFR Petten contributions to the Third World Conference on Neutron Radiography and the SITEF symposium 1989
EUR 12727 EN, 1990

/2/ L. Adams, P. Ellen, J.F.W. Markgraf, H.P. Leeflang
Neutron radiography inspection of relays for Space Technology Applications ESA Journal "Preparing for the Future", Vol. 3, No. 4, pages 6 - 7, December 1993

## 3.10. IRRADIATIONS OF BURNABLE POISON SPECIMENS

Irradiation of thermal neutron absorbing materials to effectively full depletion is being investigated, sponsored by private companies (project BOCADILLO). The experiment is required to investigate the dimensional changes associated with the samples, which are rectangular boron carbide zircalloy–4 cermets.

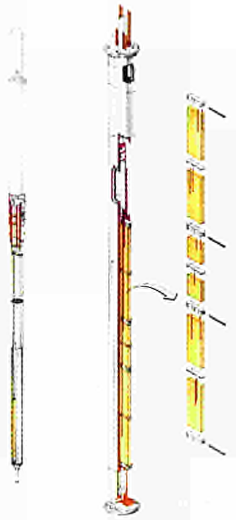


**Fig. 29**
BOCADILLO sample holder

A drawing of one sample holder, as manufactured, is shown in **fig. 29**. Samples are surrounded by sodium, in a double containment with appropriate stepped gas gaps allowing uniform temperature distribution along the axis. The temperature control is performed by means of a changeable mixture of He, Ne, $N_2$. The thermal design of the rig has been proved to be extremely accurate as shown in the example given in **fig. 30**: the heating produced by $B_4C$ depletion (variable in time), the swelling of the samples (change of gas gaps) are easily accommodated and the temperature remains constant throughout the irradiation duration (6 cycles in the reporting period).

A summary of the experiment characteristics is given in **table 21**.

Post irradiation examinations for the experiment BOCADILLO will include measurements of dimensional changes of samples, determination of $^{10}B$ depletion, measurements of density and of thermal diffusivity, SEM and TEM analysis.

**Table 21**
Status of BOCADILLO experiment

| Experiment BOCADILLO TP 262 | Temp. (K) | Irradiation start (cycle) | Irradiation end (cycle) | Fluence rate values |
|---|---|---|---|---|
| TP 262-01 | 573 | 93.06 | 94.02 | $1.87 \times 10^{18}$ $m^{-2}$ $s^{-1}$ ($\Phi_{th}$)<br>$2.68 \times 10^{18}$ $m^{-2}$ $s^{-1}$<br>($\Phi_f$ (E> 1 MeV)) |
| TP 262-02 | 603 | 93.06 | 94.02 | |
| TP 262-03 | 573 | 93.06 | 94.02 | |

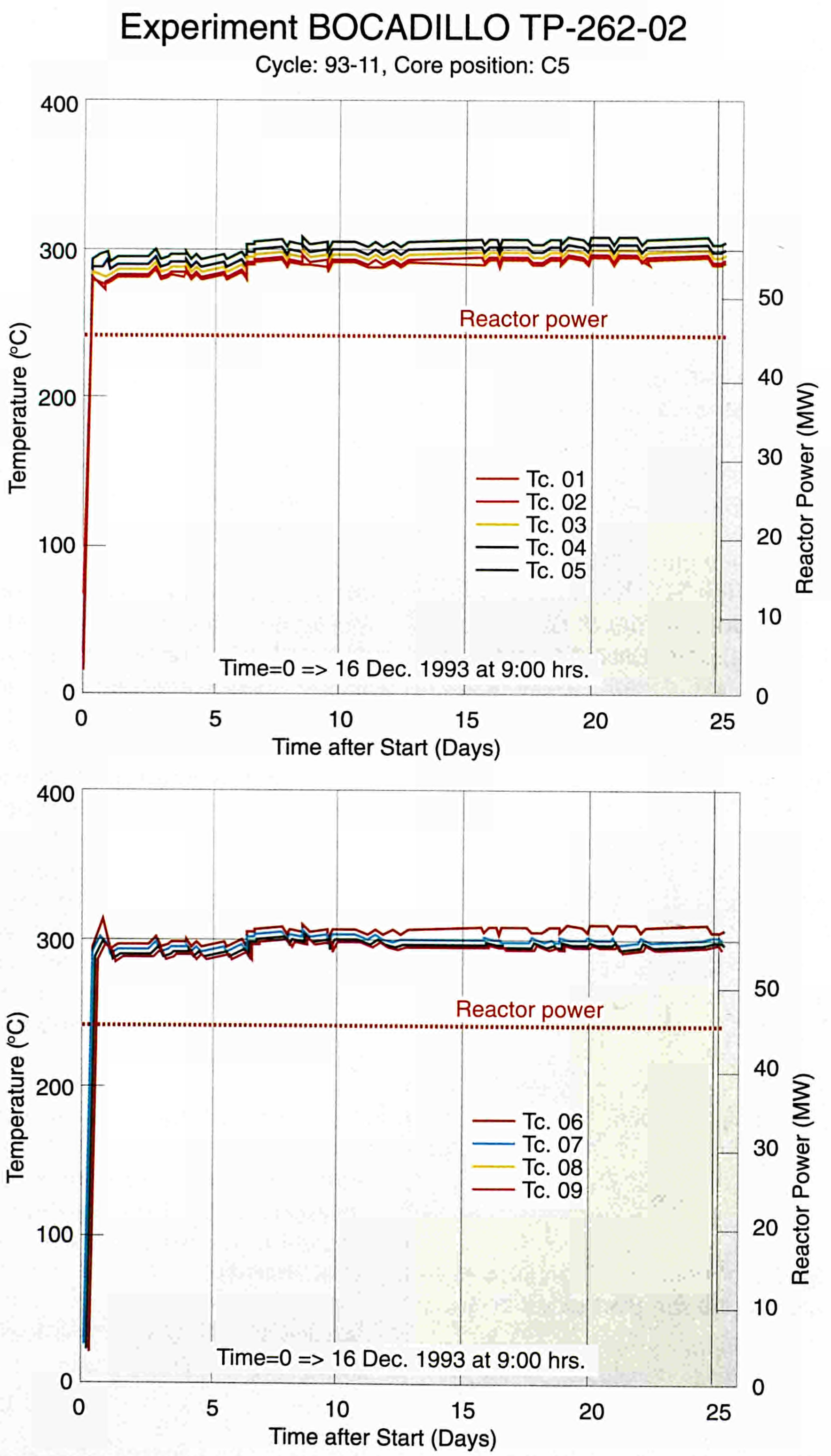


**Fig. 30**
Experiment BOCADILLO, cycle 93.11

## 3.11. CANDU MATERIAL IRRADIATIONS

The objective of this experiment (project ZIRCAN) is to demonstrate that cold worked Zr2.5 Wt%Nb tubing will withstand the diametral strain from operation without failing from creep rupture. The irradiation campaign in the HFR is intended to extend the data base on material behaviour of CANDU operational conditions.

After completion of the first irradiation campaign the irradiation device containing zirconium specimens was dismantled during the summer and the specimens have undergone dimensional measurements inside the Hot Cells. Following this activity, the specimens have re-encapsulated and sodium filled in the EUROS Cell for further irradiation.

## 3.12. TRANSMUTATION OF ACTINIDES AND FISSION PRODUCTS

Experimental programme on Recycling of Actinides and Fission Products (RAS)

Partitioning and transmutation of actinides and fission products are attracting considerable attention as an option to reduce the long-term radiological impact of high level nuclear waste. Two categories of long-lived radioisotopes in the nuclear waste are distinguished:

(a) the $\alpha$-emitting actinides (Np, Pu, Am and Cm isotopes) formed in-reac tor by neutron absorption of $^{238}$U
(b) the long-lived ß-emitting fission products $^{99}$Tc and $^{129}$I.

The beta-emitting fission products are among the important long-lived nuclides in high-level waste, which dominate the beta radiotoxicity after long disposal times. Transmutation of $^{99}$Tc and $^{129}$I by neutron capture will yield the stable isotopes $^{100}$Ru and $^{130}$Xe, respectively, and thus largely reduce the beta radiotoxicity.
ECN Petten has started in 1992 the RAS programme, in which the technological aspects of transmutation of actinides and long-lived fission products through neutron capture for a heterogeneous scenario in existing or future power reactors will be investigated /1,2,3/. Irradiation experiments at the HFR Petten are being designed in close co-operation with IAM Petten. The ECN activities are part of a European collaboration, codename EFTTRA (Experimental Feasibility of Targets for Transmutation) which has been set up to study the technological aspects. The EFTTRA partners are ITE Karlsruhe, CEA Cadarache, KfK Karlsruhe, EDF Paris & Lyon and ECN Petten. Terms for collaboration were discussed in 1993. The objectives of the EFTTRA collaboration are:

(a) Common manufacture of targets for transmutation,
(b) Irradiation of identical samples at the HFR Petten and at Phenix,
(c) Post-irradiation examinations at Petten, Karlsruhe and Cadarache,
(d) Supporting analysis on physical, chemical and material aspects.

Work for the first RAS experiment at the HFR Petten progressed as planned. The RAS-1 test is aimed to investigate the transmutation efficiencies of technetium ($^{99}$Tc) and metal iodide targets, based on natural $^{127}$I. Besides transmutation efficiencies, other aspects as self shielding, fractional xenon release of iodide targets, swelling of technetium targets, target – cladding interactions and material behaviour will be investigated during post-irradiation examinations. The technetium samples were prepared by ITE Karlsruhe and the metal iodide samples were prepared by ECN Petten. The test matrix and requirements for the first RAS experiment are given in **table 22**. Irradiation is planned in 1994 for a period of eight HFR cycles in a central core position.

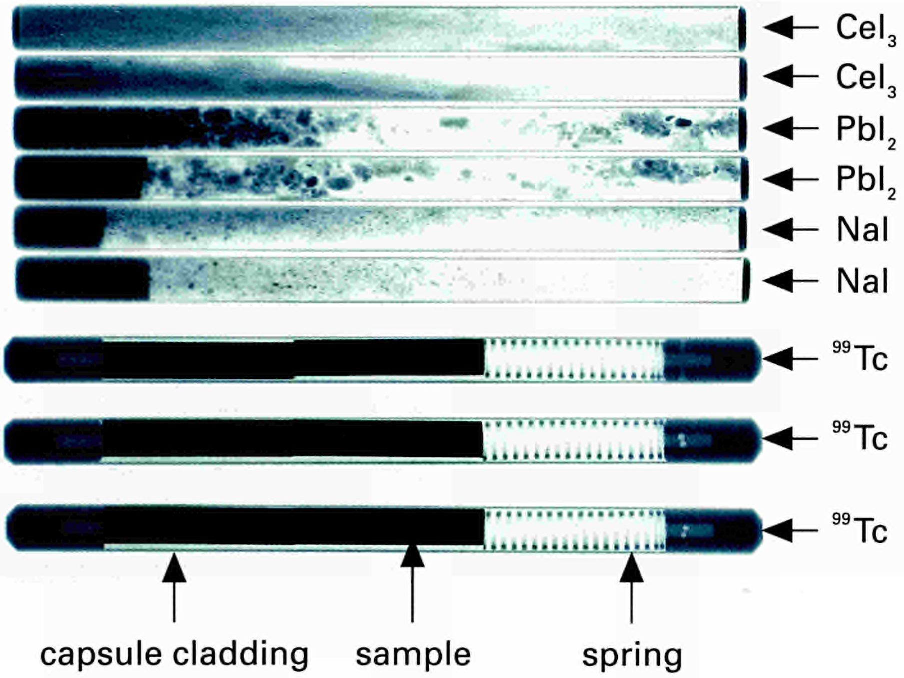


**Fig. 31**
X-ray images of capsules for first RAS experiment. Six capsules are filled with candidate iodides and three capsules are loaded with each two technetium rods of 5 mm o.d. and 25 mm length.

| Capsule no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Material | $^{99}Tc$ | $CeI_3$ | $CeI_3$ | $^{99}Tc$ | $PbI_2$ | $PbI_2$ | $^{99}Tc$ | $YI_3$ | $YI_3$ |
| Dimensions:<br>Capsule volume (cm$^3$) | 1.45 | 1.6 | 1.6 | 1.45 | 1.6 | 1.6 | 1.45 | 1.6 | 1.6 |
| Material volume (cm$^3$) | 0.98 | 0.75 | 0.75 | 0.98 | 0.75 | 0.75 | 0.98 | 0.75 | 0.75 |
| Melting point (K) | 2340 | 1033 | 1033 | 2340 | 683 | 683 | 2340 | 1238 | 1238 |
| Irradiation temperature (K) | | | | | ±750 | ±750 | | | |
| Transmutation efficiency (%/cycle) | ≥0.73 | ≥0.41 | ≥0.41 | ≥0.73 | ≥0.44 | ≥0.44 | ≥0.73 | ≥0.42 | ≥0.42 |
| Irradiation time (cycles) | | | | | 8 | | | | |
| Max. gas pressure due to xenon build-up (MPa) | – | 3.7 | 3.7 | – | 3.3 | 3.3 | – | 3.5 | 3.5 |

**Table 22**
Test matrix and required irradiation conditions for RAS-1.

## References

/1/ K. Abrahams, R. Conrad, W.P.M. Franken, H. Gruppelaar, R.J.M. Konings, P.J.M. Thijssen Technological aspects of transmutation of technetium and iodine Poster presentation at GLOBAL 1993, Seattle, September 12-17

/2/ W.M.P. Franken et al.
Technological aspects of transmutation of technetium and iodine
ECN-92-018, May 1992

/3/ R.J.M. Konings, W.M.P. Franken
Irradiation program for fission products and inert matrices in the HFR Engine-93-02, April 1993

# 4. GENERAL ACTIVITIES

This chapter reports on services supporting a number of projects and investments and work intended to keep equipment and competence at the required level. The general activities within the HFR programme include:

- operation and maintenance of ancillary services and laboratories
- technical support to the running irradiation programme.

## 4.1. ASSEMBLY ACTIVITIES

During the reporting period 51 in-pile and 4 PSF experiments were assembled in the assembly laboratory or by external firms; 12 of them were isotope devices.

**Fig. 32**
Assembly laboratory

The following standard in-core capsules, instrumented heads and PSF devices were manufactured:

1 Instrumentation head
4 In-core irradiation capsules
2 PSF-carriers
1 In-core irradiation capsule was modified (TRIESTE)
2 PSF-capsules

## 4.2. QUALITY CONTROL

During the reporting period the Quality Control group checked 48 irradiation devices or components and issued the related QC reports:

26 Sample holders
8 In-core capsules
2 Instrumentation heads
6 PSF experiment carriers
6 Miscellaneous

A defect safety sodium dump valve of the liquid metal filling station has been replaced by a new valve with better specifications. Also all the trace heating sections on the sodium loop were renewed. The turbo vacuum pump water cooling circuit received a shut-off valve. A new trace heating section was introduced for the filling of the loop with sodium.

The flow scheme of the experiment water flow and calibration installation has been rearranged and the circuit is completely made of stainless steel components. The available flow capacity is now up to 18 $m^3$/h.

The HFR stock of TRIO 131 capsules and dummy sample holders has been replenished.

As a nondestructive examination, Dye Penetrant has been introduced and is now used as a standard test for all the welds on safety containments. A wide range of standard crack panels is available to monitor the sensitivity of the test. The Dye Penetrant procedures were issued.

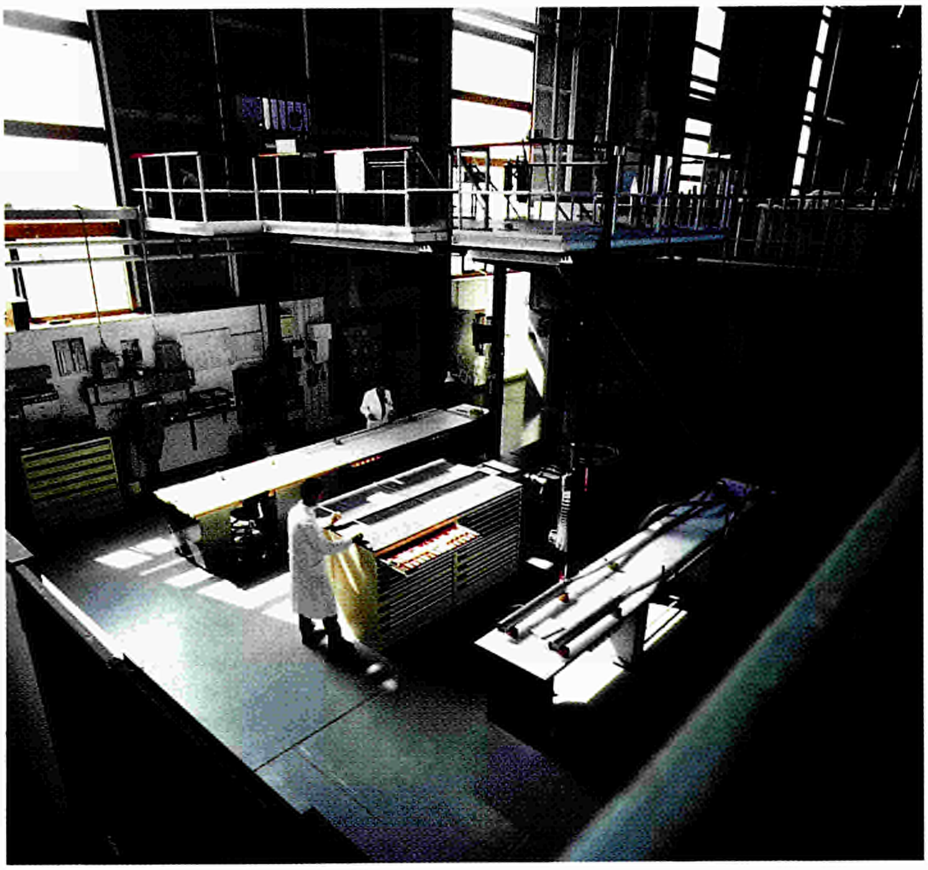


**Fig. 33**
Quality control and commissioning laboratory

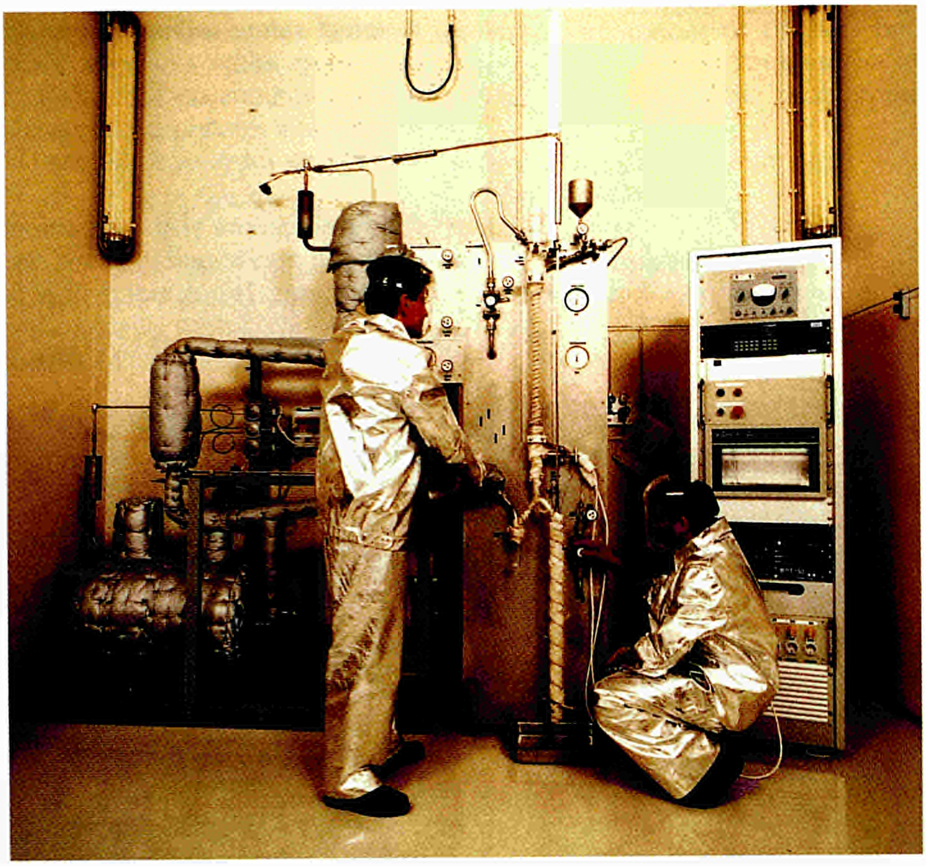


**Fig. 34**
Sodium filling of a sample holder

## 4.3. EXPERIMENT OPERATION

During the 11 cycles of 1993 3 TRIESTE sample carriers, 4 REFA and 13 TRIO sample holders were loaded into the respective reloadable irradiation devices for in-core irradiation; 3 TRIESTE sample carriers, 3 REFA and 17 TRIO/QUATTRO sample holders were unloaded and prepared for dismantling.

The PSF irradiation devices for the RELIEF experiment have ended their irradiation campaign, and have been prepared for post-irradiation measurements. KAKADU sample holders have been installed and successfully irradiated.

A new radioisotope device PROMETEO has also been installed.

## 4.4. HOT CELLS AND POST-IRRADIATION WORK

*Dismantling Cell*
The cell team provided the following services:
- Dismantling of 58 radioisotope capsules
- Dismantling of 40 irradiated experiments
- Disposal of reactor components (section of fuel elements and control rods)
- General repair of cell equipment (transport container, cutting device, manipulators)
- Dismantling of 3 TRIO, 3 REFA and 1 QUATTRO capsules
- Change of all cell filters
- Transport of special experiments from the EUROS Cell to the HFR

45 Internal and external transports of radioactive waste and samples have been executed, and 45 neutron radiography images have been taken of irradiated fuel pins and sample holders.
Updating of the safety report of the DM Cell has been started and is in progress.

*EUROS Cell*
The purpose of this cell is to carry out remote Na-filling and welding in order to re-encapsulate irradiated samples.During the reporting period the following remote re-encapsulations where carried out:

- POUSSIX
  Three FBR fuel pins have been successfully remote encapsulated in the EUROS Cell.
- ZIRCAN
  After a complete transformation of the equipment of the EUROS Cell a first cold encapsulation was executed with Zr dummies to check the installation and the chosen procedure.After that the re-encapsulation of ZIRCAN-02 was successfully performed on schedule.

*G4 Cell*
Two measurement series of pre-irradiated TRIESTE samples have been performed in this cell.

## 4.5. JOINING TECHNIQUES

The Joining Techniques group provided various services like routine weldings for sample holder assembly and specific weldings for irradiation devices fabricated at outside firms.
A laser welding machine was installed and put into operation.
More than 9000 wires for medical applications were top welded.
During the reporting period a new orbital welding machine was installed in the EUROS Cell.

## 4.6. PROGRAMME MANAGEMENT AND MISCELLANEOUS

*Planning*

During the reporting period the HFR Planning Meeting was held three times and three editions of the loading chart were issued (HFR/36 to HFR/38).

*Seminars organized by the HFR Unit:*

J. Ahlf, IAM Petten
Research Reactors, A Worldwide Overview
25 February 1993

E. Sabbioni, JRC Ispra
Metallotoxicology Research at the JRC-Ispra
Present trends and perspectives for the future
26 March 1993

G. Schmitz, KfK, Institut für Reaktorsicherheit
Radiation Induced Electrical Degradation (RIED)
20 April 1993

A.W. Mehner, Siemens, UB KWU, Hanau
Quality Assurance Assessment of Subcontractors
Application of EN 29001
22 April 1993

Prof. Hwai-Pwu Chou, National Tsing Hua University, Taiwan
Overview of nuclear industry in Taiwan
26 May 1993

A. Zurita, IAM Petten
The Integral Quality Assurance Handbook (HFR-IQAD) and the concept Safety Culture
2 December 1993

R. Konings, ECN
Irradiation tests of transmutation of actinides and fission products in the HFR: Background and Prospectives
9 December 1993

*Participation in Exhibitions*

The HFR Unit participated in the following exhibitions:

Exhibition in the framework of TOPNUX '93
International ENS Topical Meeting
Towards the Next Generation of Light Water Reactors
The Hague, April 25-28, 1993

**Fig. 35**
Minister Andriessen visits the TOP-NUX'93 exhibition

Technical exhibition in the framework of SMiRT 12
12th International Conference on Structural Mechanics in Reactor Technology
Stuttgart, August 15-20, 1993

*Visiting Group Evaluation*

An evaluation of the HFR programme has been performed by a "Visiting Group" appointed by the Board of Governors of the JRC. The Visiting Group was composed of recognized independent experts, with a scope focused on

- performing an evaluation of all managerial, operational and exploitation activities of the HFR,
- assessing the scientific quality, efficiency and appropriateness of the work, and
- providing advice on the ongoing work.

An important outcome of this evaluation was that the HFR meets its principal scientific and technical objectives set out in the Council Decision No. 92/275/Euratom of 29 April 1992.

According to the Visiting Group Report, the operation of the HFR has been carried out with high technological standards, good operational performance, excellent safety record and high degree of customer satisfaction.

# 5. QUALITY ASSURANCE

The specific organizational structure **(fig. 36)** and nature of the activities at the HFR links the concept Quality Assurance to the one of Safety Culture. The main means to develop both concepts are the "Work and Action Plan for HFR Petten" and the set-up of the "HFR Integral Quality Assurance Handbook". The state and progress of both are herewith reported.

## 5.1. WORK AND ACTION PLAN FOR HFR PETTEN

The "Work and Action Plan for HFR Petten", which resulted from the "Kernfysische Dienst" inspection of 1988, comprises fifty five requirements and has been further updated. The fulfilment of these requirements was continued in close co-operation between the HFR Unit of JRC-IAM and the HFR Group of ECN-NUC. The completion of one requirement is still pending, fourteen are ongoing activities and the rest are completed. All these items, completed or ongoing activities, have been incorporated into the "HFR Integral Quality Assurance Handbook" (HFR-IQAD).

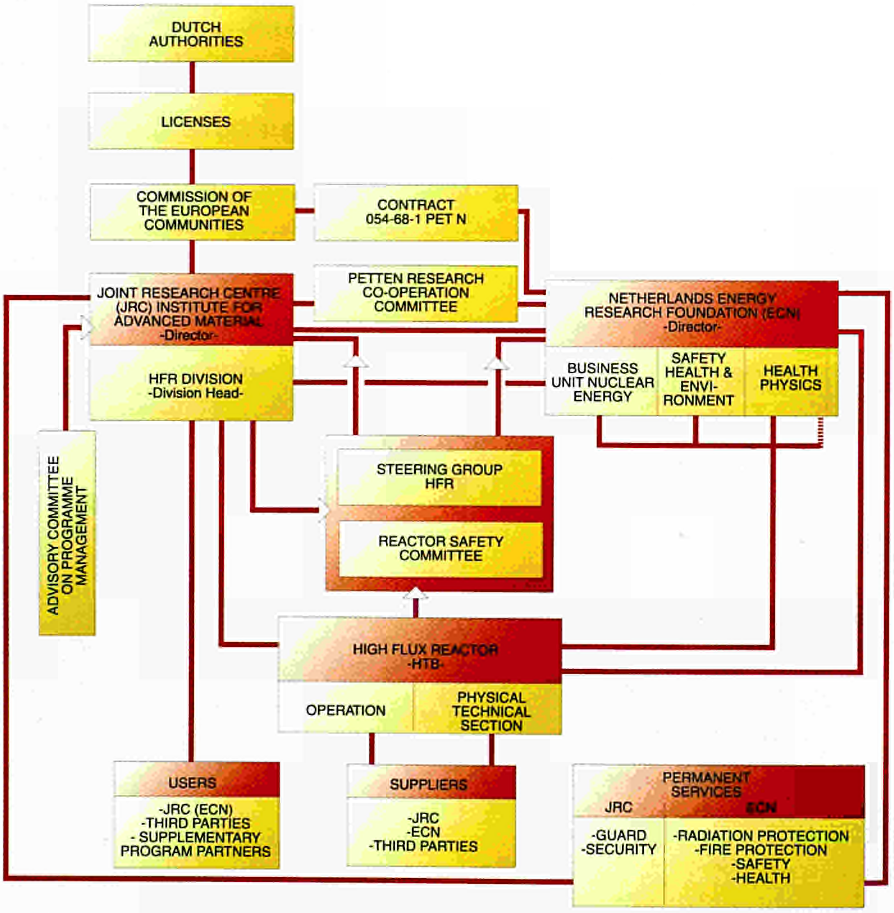


**Fig. 36**
Relation scheme HFR operation & exploitation

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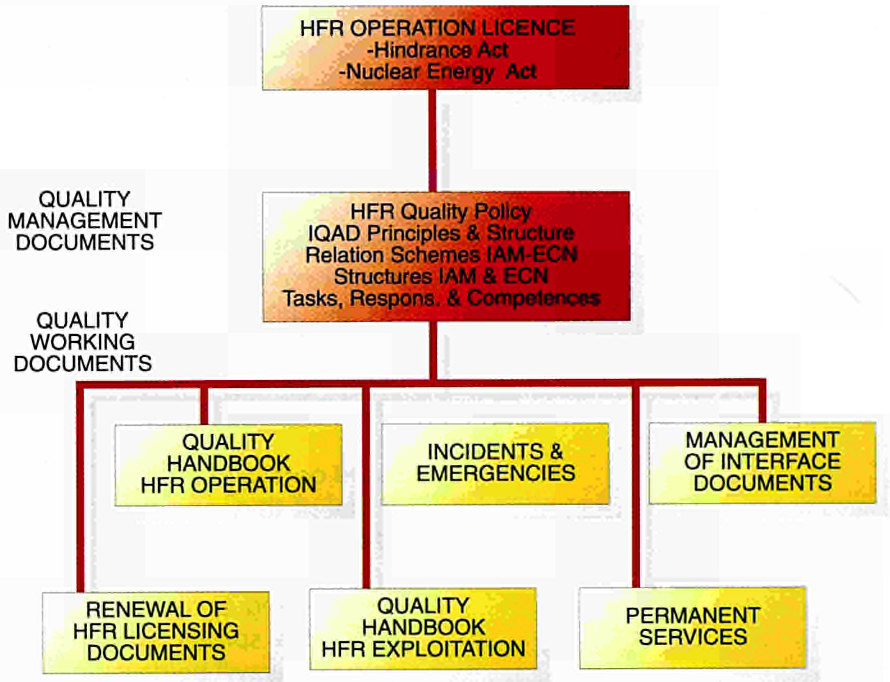
## 5.2. INTEGRAL QUALITY ASSURANCE HANDBOOK

The implementation of a consistent and comprehensive HFR-IQAD has been continued. There are three levels of documents, the two main of them, i.e. quality management and quality working levels, are shown in the diagram of **fig. 37**. To those two levels, a third one is ordered below, including a wide range of documents used to prescribe the specific details for the conducting of tasks performed by individuals or small functional groups or teams, i.e. working procedures, instructions or regulations to cover different activities, design, assembly operations, test and maintenance, calibration, quality control activities, etc.

**Fig. 37**
HFR-Integral Quality Assurance Handbook (HFR-IQAD)



Within the frame of the quality management documents, the objectives and safety policy of the HFR, as well as the structure and deputy regulations of both involved organizations, HFR Unit of JRC-IAM and HFR Group of ECN-NUC, were issued. The quality documents regarding the HFR operation licence, the HFR quality policy, the principles and structure of HFR-IQAD, as well as the tasks, responsibilities and competences of specific staff are ready in a draft form.

The renewal of the technical safety documentation DOKPAK is ordered within the frame of the quality working documents. In this sense, the already operational "Technical Description of the HFR Installation" is being updated continuously, also in order to incorporate system modifications. The other two main documents, i.e. the "HFR Safety & Accident Analysis" and the "HFR Safety & Technical Specifications" have been subject of revision, the first of them also by an external company. These two documents will be the basis for the public "Design & Safety Report of HFR".

The QA system for HFR operation has been further improved. An update of several procedures is in progress to adapt the "Quality Handbook for HFR Operation" as a quality working document of HFR-IQAD.

Additional effort has been contributed to formalisation of procedures for planned periodical maintenance, to update technical documentation in general and especially after replacements and modifications. Implementation of the computerized maintenance management system proceeded further.

Within the frame of the "Quality Handbook for the HFR Exploitation", underlying quality working document of HFR-IQAD, six different procedures have been issued. In this context, twenty Design and Safety Reports related to experiments have passed the internal review of the IAM HFR Unit during 1993.

A framework for a technical education and training programme ("Integraal Opleidings Plan") for all ECN personnel involved in operation and maintenance of the HFR has been defined during 1993. Further implementation is foreseen in 1994. Preceding this (and following already existing practice for HFR operation personnel) a course was organised during the 1993 reactor stop. This course is meant to familiarize all HFR personnel with the Dutch Nuclear Safety Rules on quality assurance. The course was presented by a specialised outside firm.

Based on the "Technical Training Plan for the HFR Unit Staff of JRC-IAM" a total of thirteen courses on radiological protection (some of them organized by ECN) have been attended.

The Working Group on Welding Specifications has finished the development of a specific working document, from which further operational instructions will be developed.

# 6. SUMMARY

In 1993 the HFR was in operation during 279 days which corresponds to an overall availability of 76%. Routine maintenance and modification activities were carried out in the two main stop periods. Good progress was made in the scheduled upgrading projects.

The average utilization of the HFR was 60% of the practical occupation limit. The reactor was utilized for research programmes in support of nuclear fission reactors and thermonuclear fusion, for fundamental research with neutrons, for radioisotope production (mainly for the medical sector), for BNCT, and for various smaller activities.

Work in support of the irradiation programmes, such as assembly of rigs, quality control, experiment operation and PIE and hot cell work, continued as normal.

As a matter of high priority, further significant efforts were made with regard to quality assurance. A significant number of documents belonging to the HFR Integral Quality Assurance Handbook has been issued.

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# GLOSSARY

| | |
|---|---|
| AMCR | Acier Mangan Chrome (Low activation material) |
| BNCT | Boron Neutron Capture Therapy |
| BOCADILLO | BOron CArbide irraDIation for RoLLs ROyce |
| BOL | Beginning Of Life |
| BWFC | Boiling Water Fuel-element Capsule |
| BWR | Boiling Water Reactor |
| CARIATIDE | CAmeRa IrrAdiaTIon in neutron fielD for jEt |
| CATETO | CompAct TEnsion and Tensile specimens irradiatiOns |
| CEA | Commissariat à l'Energie Atomique |
| CEN | Centre d'Etudes Nucléaires |
| CERAM | net CERAMics |
| CFC | Carbon Fibre Compound |
| CHARIOT | CHARpy and compact tensIOn specimens irradiaTion |
| CT | Compact Tension (specimen) |
| DACOS | Data Acquisition and Control On-line System |
| DIN | Deutsche Industrie Norm |
| DM | Dismantling Cell |
| ECN | Energieonderzoek Centrum Nederland |
| EDN | Equivalent DIDO Nickel fast neutron fluence |
| EFR | European Fast Reactor |
| EFTTRA | Experimental Feasibility of Targets for TRAnsmutation |
| ENEA | Ente Nazionale Energie Alternative |
| EOL | End Of Life |
| EPIRO | EPoxy resIns iRradiatiOn |
| EUROS | European Remote encapsulation Operating System |
| EWGIT | European Working Group on Irradiation Technology |
| EXOTIC | Extraction of Tritium in Ceramics |
| FACHIRO | FACility with HIgh flux for Radioisotopes prOduction |
| FARO | FAst fluence Rate relOadable facility |
| FBR | Fast Breeder Reactor |
| FURIAE | FUsion Reactor materials IrrAdiations for ECN |
| HF-PIF | High Flux Poolside Isotope Facility |
| HFR | High Flux Reactor |
| HIP | Herlaadbare Isotopen Productie faciliteit |
| HTR(HTGR) | High Temperature Reactor |
| IAEA | International Atomic Energy Agency |
| IAM | Institute for Advanced Materials |
| ILAS | Irradiation of Low Activation Specimens |
| ISOLDE | Iodine Solubility and Degassing Experiment with pre-irradiated PWR fuel rods |
| JAERI | Japenese Atomic Energy Research Institute |
| KAKADU | Kamin Kasel-Duo (Twin capsules for fuel pin irradiation) |
| KFA | Kernforschungsanlage Jülich |
| KFD | Kernfysische Dienst |
| KfK | Kernforschungszentrum Karlsruhe |
| KWU | Siemens AG, UB KWU |
| LEU | Low-enriched Uranium |
| LIBRETTO | LIquid BReeder Experiment with Tritium Transport Option |
| LOCA | Loss of Cooling Accident |
| LOF | Loss-Of-Flow |
| LWR | Light Water Reactor |

| | |
|---|---|
| MANIA | MANet IrrAdiations for ECN |
| MANITU | MANet IrradiaTions for fUsion applications |
| MOX | Mixed Oxide |
| MYKONOS | MolYbdenum production for MallincKrOdt DiagNOStica |
| NAST | Na-steel irradiation |
| NET | Next European Torus |
| NILOC | NItride fuel, Low in Oxygen and Carbon |
| NRWG | Neutron Radiography Working Group |
| OPOST | Overpower steady/state irradiation |
| ORNL | Oak Ridge National Laboratory |
| PHWR | Pressurized Heavy Water Reactor |
| PIE | Post-irradiation Examinations |
| PIF | Pool side Isotope Facility |
| PLC | Programmable Logic Controller |
| POMPEI | Pellets Oxyde Mixte, PEtten Irradiation |
| POTOM | Power to melt irradiation |
| PROF | Pool Side Rotating Facility |
| PROMETEO | PROduction of MolybdEnum by fissile TargEt irradiatiOn |
| PSF | Pool Side Facility |
| PWR | Pressurized Water Reactor |
| QA or Q/A | Quality Assurance |
| QC | Quality Control |
| QUATTRO | Four channel reloadable rig (29mm) |
| RAS | Recycling of ActinideS and fission products |
| R&D | Research and Development |
| REFA | Reloadable Facility |
| RELIEF | FBR fuel/cladding, axial displacement measurement experiment |
| RIF | Reloadable Isotope Facility |
| RODEO | ROtating DEvice for radiOisotope production |
| SCK | StudieCentrum voor Kernenergie (Mol,B) |
| SEM | Scanning Electron Microscopy |
| SICOMORO | SIlicon COMpOsites iRradiatiOn |
| SINAS | Simplified NAST (irradiation capsule) |
| SIRIO | Shielded IRradIatiOns |
| SIWAS | SImplified WAter-Steel irradiation |
| SOFT | Symposium on Fusion Technology |
| SURP | SURveillance Programme |
| TEDDI | Computer programme to evaluate reactor neutron spectrum |
| TEM | Transmission Electron Microscopy |
| TIRO | Thermal fluence rate reloadable IRradiatiOn facility |
| TOP | Transient Overpower |
| TRIESTE | TRIO Irradiation with Experiment of Steel-Samples under Tension |
| TRIMURTI | TRIo Modified for fUsion Reactor maTerials Irradiations |
| TRIO | Irradiation Device with three thimbles |
| TRISO | Coated HTR fuel particle types |
| ZIRCAN | ZIRconium specimens for CANada |

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ABSTRACT

In 1993 the HFR was in operation during 279 days which corresponds to an overall availability of 76%. The average utilization of the reactor was 60% of the practical limit. The reactor was utilized for research programmes in support of nuclear fission reactors and thermonuclear fusion, for fundamental research with neutrons, for radioisotope production, for BNCT, and for various smaller activities. General activities in support of running irradiation programmes progressed in the normal way. Further significant efforts were made with regard to quality assurance.

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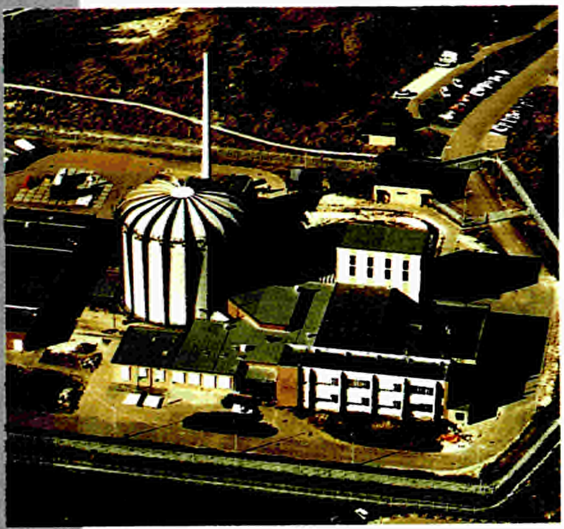

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