Postirradiation Testing of High Temperature Reactor Spherical Fuel Elements Under Accident Conditions

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A new furnace for accident condition testing of spherical high temperature reactor fuel elements has been installed and now operates in the hot cells of the Institute for Transuranium Elements (ITU) Karlsruhe. The recent apparatus was constructed on the basis of a former development by Forschungszentrum Jülich (Schenk, Pitzer, and Nabielek, 1988, "Fission Product Release Profiles From Spherical HTR Fuel Elements at Accident Temperatures," Jülich Report No. 2234), where it was named KüFA, the German acronym for cold finger apparatus. In a preceding publication (Kostecka, Ejton, de Weerd, and Toscano, 2004, "Post-Irradiation Testing of HTR-Fuel Elements Under Accident Conditions, Part 1 and 2," Second International Topical Meeting on High Temperature Reactor Technology, Beijing, China) the general concept and details of the device were described. The present paper reports on the first operation under hot conditions, and the calibration of the fission gas measurement and of the efficiency of the cold finger, which is used to plate out solid fission products. Finally the results of fission product release and analysis of two heating tests on two fuel elements from the high temperature reactor K6 irradiation experiment (Nabielek, Conrad, Roellig, and Meyers, 1993, "Fuel Irradiation Experiments on HFR-K6 and HFR-B1 With Intermittent Water Vapour Injections," Technical Committee Meeting on Response of Fuel, Fuel Elements and Gas Cooled Reactor Cores Under Accidental Air or Water Ingress Conditions, Beijing, China, Oct. 25–27) are presented and discussed. [DOI: 10.1115/1.3094020]

1 Introduction

Increasing prices for fossil energy sources and the need to reduce CO_2 emissions lead to a new interest in nuclear power generation worldwide. A major issue remains the acceptance of nuclear energy by the public, especially concerning the safety of operation, waste disposal, and proliferation aspects. High temperature reactors (HTRs), being inherently safe against nuclear power excursions and by means of passive decay heat removal without destruction of the core, can meet the requirement of safe operation.

The HTR safety concept is based on the retention of the fission products in the fuel under operational and accidental conditions. Due to the low core power density, high thermal core mass, and high surface to power ratio, a carefully constructed HTR can be inherently safe by means of passive decay heat removal without destruction of the core. In particular, high quality coated particle fuel can withstand such accident temperatures without significant release of fission products. In order to investigate and verify performance limits and quality of HTR coated particle fuel at different burn-ups, experimental data are needed. A simple way to obtain such data is to simulate a reference accident scenario (e.g., the loss of all active heat sinks) with a furnace, to measure the released fission gases and to determine the fission product inventories of the samples before and after heating [1]. Samples can be individual irradiated coated particles but also complete spherical fuel elements or compacts. An advantage of testing the whole fuel element is the excellent statistics by testing thousands of coated particles at the same time. Besides the integral values of released fission products, the time dependence of fission product release and individual particle failure are also important to understand the underlying mechanisms. For modern TRISO coated particle fuel, only a small release of gaseous and solid fission products in the order of 10^{-6}–10^{-5} fractional release can be expected under accident conditions. Such releases are usually far smaller than the uncertainty associated with the measurement of a fuel element by gamma spectrometry [2]. If more accurate values and time dependent information are needed, a method has to be used to collect the released solid fission products during regular intervals followed by separate measurements. For this purpose a special furnace was constructed at the beginning of the 1980s in Forschungszentrum Jülich (FzJ), the "cold finger device," or in German, Kühlfingerapparatur (KüFA). After it was decided to abandon research on HTR technology in Germany, a KüFA was transferred from FzJ to Institute for Transuranium Elements (ITU), where it was installed in a hot cell.

KüFA was designed as a metallic furnace with a movable water-cooled cold finger in order to condense solid fission product vapors and with a gas sweep system, which conveys released fission gases outside the hot cell for measurement. The furnace is heated via direct electric resistance heating. All inner parts are made of tantalum. The fuel element temperature is monitored with a W/Rh thermocouple positioned 3 mm below the sphere. According to the manufacturer the system is able to perform heating curves up to 2000°C. However, since the risk of damaging inner parts increases significantly at higher temperatures, the highest temperature programmed until now was 1800°C. The cold finger is positioned directly over the fuel element. At the bottom of the cold finger a cold plate is fixed. The cold plate can be changed during the test and can be measured afterwards for deposited fission products.

The calibration of the cold finger efficiency and the analytical methods used to measure the cold plates are presented in this

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paper. The gaseous fission products are transported from the furnace to a charcoal cold trap, cooled with liquid nitrogen, where they condense and where they can be detected online by gamma spectrometry using a 3×3 sodium-iodide (NaI) gamma detector.

The new KüFA at ITU is equipped with a fully automated monitoring and controlling system for all relevant parameters. Efficient and electronically-regulated water cooling of the cold finger ensures constant conditions independent of the environment and helps guarantee the reliability of the results. A more detailed description of the KüFA furnace, the cooling system, and the controlling system can be found in a preceding publication [3]. After successful installation of the KüFA in the hot cells, two irradiated spherical fuel elements from the Jülich research reactor Arbeitsgemeinschaft Versuchsreaktor (AVR) (Jülich, Germany) and two fuel elements from the high flux reactor (HFR) K6 irradiation in Petten, the Netherlands [4] were heated and the respective fission product release was measured. Preparation, performance, and results of these tests are presented in this paper.

2 Testing Procedure

The typical testing procedure should simulate as close as possible the accident scenario following the loss of all active heat sinks during normal operation. In order to clean the helium circuit the system is purged with helium at room temperature for several hours. After this a short heating phase of 6 h at 300°C is programmed in order to remove moisture from the fuel element and the furnace interior. Next a reactor simulation phase at 1050°C for 10 h follows in order to reach the same equilibrium state, as would occur in the reactor. The transients between the first phases are approximately 600°C/h. From 1050°C the temperature is increased by 47°C/h to 1600°C (or higher) according to HTR Modul® [5] accident simulations with depressurization and loss of forced cooling. After the accident simulation, the temperature is decreased to room temperature at a rate of approximately −100°C/h. The pressure inside KüFA is kept at 980 mbar throughout the experiment.

3 Fission Gas Measurement

When fission gas is released from a fuel element during a KüFA test, it is distributed into the inner volume of the furnace ($V_G \sim 28.6$ l). From there it is transported together with the sweep gas (helium) to the cold trap outside the hot cell, where it condenses at −195.8°C. The helium flow is 30 l/h under standard conditions. Thus, the equation describing the activity built-up in the cold trap after a sudden release of fission gas, as would occur in case of a complete failure of a coated particle, can be derived

$$A_{\mathrm{CT}}(t) = A_{G,0} \cdot (1 - e^{((-\dot{V}_{\mathrm{He}} T_G / V_G T_U) \cdot t)}) \tag{1}$$

where $A_{\mathrm{CT}}(t)$ is the activity in cold trap (Bq), $A_{G,0}$ is the released activity from coated particle (Bq), $\dot{V}_{\mathrm{He}}$: helium flow (l/h), V_G is the furnace volume (l), T_G is the furnace temperature (K), and T_U is environment temperature (K).

The increasing activity in the cold trap is monitored by a NaI detector. In fuel elements stored over a long time since irradiation only the noble fission gas Kr-85, with its long half life of 10.77 years, is left in non-negligible amounts. For fuel elements coming from a recent irradiation Xe-133 (half life of 5.423 days) might also be detectable (Fig. 1). The calibration of the fission gas measurement was done by introducing a known amount of Kr-85 from a commercial standard into the gas circuit before passing through the KüFA. The increasing activity in the cold trap was monitored with a continuous series of scans (see Fig. 2). Each scan was performed for 3 min. Expected and measured activities were in good agreement.

Before performing a calibration, a background measurement of the environment and an energy calibration of the NaI detector are performed. Spectrum analysis is done automatically using InterWinner® [6]. A calibration factor (f_C) can be derived using the following formula:

$$\dot{I} = \frac{A_{\mathrm{CT}}}{f_C} \tag{2}$$

where $\dot{I}$ is the number of impulses per second, A_{CT} is the activity in cold trap, and f_C is the calibration factor.

An individual calibration factor is determined for each heating test by performing one calibration of the circuit before and one after the heating procedure. Additionally a calibration is performed by introducing an aliquot directly into the cold trap, in order to ensure that not only the efficiency of the cold trap is calibrated but also the tightness and efficiency of the whole system are guaranteed.

In order to prevent any loss of data a second cold trap with a separate NaI detector is placed in the circuit behind the first one. If the charcoal in the first cold trap is saturated with Kr, an activity increase in the second trap will be registered. After a heating test

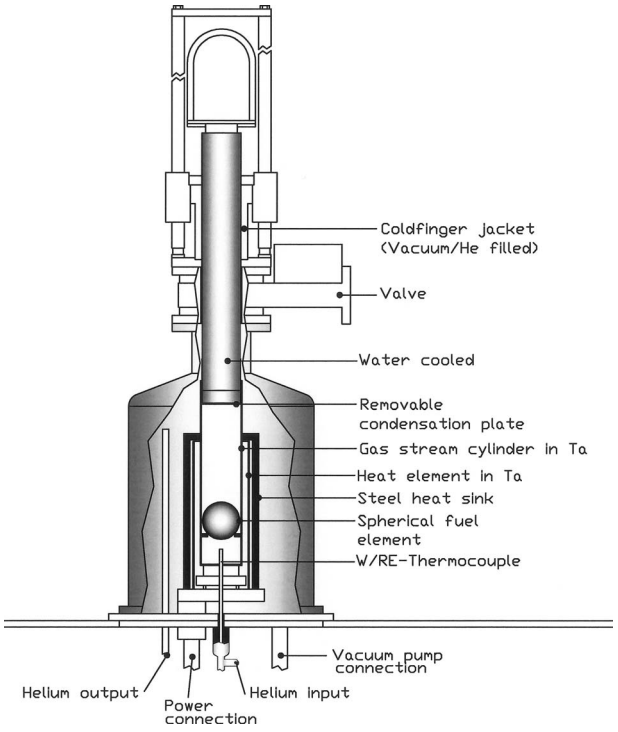

Fig. 1 Cold finger device

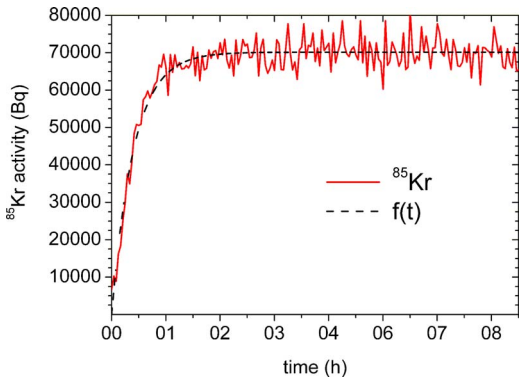

Fig. 2 Calibration curve for fission gas measurement

the cold traps are heated up to 300°C under a constant helium flow in order to remove the Kr-85 and to reactivate the charcoal.

The detection limit of the fission gas measurement system for Kr-85 is in the order of 700 Bq. A coated particle failure would lead to a Kr-85 release in the order of 10^5 Bq. Subsequently, Kr-85 would diffuse through the matrix graphite and be released into the furnace atmosphere. Following diffusion theory a break through time, t_D, through the graphite matrix can be estimated [7]

$$t_D = \frac{r^2}{6D_{\mathrm{Kr}}}$$

According to Ref. [8] the diffusion coefficient of Kr in A-3 graphite along the grain boundaries is $D_{\mathrm{Kr}} > 10^{-5}$ m^2/s. Therefore, a pressure vessel failure of a coated particle (in the center of a pebble with a 3 cm radius) would cause the release of Kr from the fuel element almost immediately (15 s). The delay between furnace and cold trap amounts 3–4 min at the usual flow rates. Knowing the activity build-up function in the cold trap (see Eq. (1)) the exact time of a particle failure during a KüFA test can be determined.

The uncertainty of a 3 min measurement of the cold trap activity is quite high. In order to obtain a reasonably smooth curve, the raw data from the scans are smoothed manually, applying the moving average of 50 scans after the test.

4 Cold Plate Analysis

Volatile solid fission products, such as, e.g., Cs-134, Cs-137, Sr-90, and Ag-110m, are released from the fuel element during a heating test and are condensed onto the exposed bottom surface of the cold plate. Each cold plate is introduced into the cell in a clean aluminum container with an individual identification number. Placing and replacing the cold plates from the cold finger are done without direct contact between cold plate and manipulator. The plate comes only in contact with the aluminum container and the cold finger. If the activity of the cold plates is low enough, they can be transported outside the cell where the aluminum containers, contaminated in the cell, are replaced by fresh containers, thus minimizing the contamination chances of the plates. Finally, the plates inside the clean aluminum container are placed in front of a high purity germanium detector in a defined geometry and are measured.

5 Cold Finger Efficiency

During a KüFA heating test the temperature of the cold plate surface is kept at 65°C. Solid fission products condense on the plate with specific efficiencies. Relevant solid fission products are mainly Cs-134, Cs-137, I-131, Sr-90, and Ag-110m. Experiences with the old KüFA in Jülich showed an average cold finger efficiency for Cs and Ag of about 70% and of about 20% for Sr [5]. Since geometry and inner conditions are the same for the new KüFA, it was assumed that the efficiency should be the same. In order to prove this assumption, several calibrations were performed.

The cold finger efficiency for Cs was determined using commercial Cs-137 standards. A standard glass vial containing the Cs standard was placed in a spherical graphite crucible with a large hole penetrating into the center, and was closed with a graphite screw that matched the hole. The crucible was produced from a graphite sphere having the same dimensions as a fuel element (see Fig. 3). A hole was drilled through the screw, and an aluminum plate was fixed between screw and ampoule. Afterwards the whole crucible was placed into KüFA, and a heating program was started up to 1600°C in the shortest time possible. The aluminum plate melts at, and the Cs evaporates into the furnace atmosphere.

The calibrations were performed with the furnace at 1600°C for 3 h. Afterwards, the cold plates were transferred into a low activity laboratory and measured by gamma spectrometry. Before and between the calibrations, heating programs of up to 1600°C without a standard were performed. This was done in order to determine the background contamination of the device and to exclude memory effects between the calibrations. The average efficiency was obtained by calculating the mean average of the measured activities on the plates minus the average background divided by the introduced standard activity (see Eq. (3))

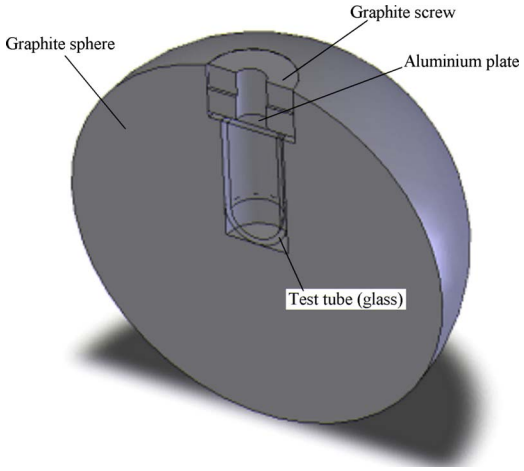

Fig. 3 Crucible for efficiency determination

$$E_{KF} = \frac{\sum_i E_{KF,i}}{i} = \frac{\sum_i \frac{A_i - C_i}{A_{n,i}}}{i} \tag{3}$$

E_{KF} is the cold finger efficiency, A_i is the activity on cold plate i, $A_{n,i}$ is the introduced standard for calibration i, and $C = \sum_j C_j / j$: average background.

The efficiency for Cs, E_{KF}, was determined, in agreement with the Jülich indications, as 70% with an extended uncertainty (95% confidence) of ±16%. Since the cold finger efficiency for Cs is in good agreement with FzJ results, it is assumed that this is also the case for other species.

6 Operation Under Hot Conditions

6.1 AVR 73/21. In 2005 the commissioning of KüFA was completed, and several cold tests were performed for all subsystems. Subsequently a first irradiated fuel element from the AVR reactor with low burn-up was loaded into the furnace, and a heating program up to 1800°C was started (Table 1).

The fuel element inventory at beginning of the KüFA test was calculated according to given burn-up of 2.5% fissions per initial

Table 1 Fuel element data for AVR 73/21

ID No.	AVR 73/21
Type	GLE-3
Graphite	A3-27
Fuel particles	16,400
Heavy metal	10 g
Fuel composition	UO_2
Enrichment	9.82% U-235
Burn-up	2.5% FIMA
Irradiation time	235 EFPD
End of irradiation	February 1984
Irradiation temperature	~700°C
Fluence	
Thermal	2×10^{21} cm^{-2}
>0.1 MeV	4×10^{20} cm^{-2}

Table 2 Fission product inventory of AVR 73/21

Cs-137	Cs-134	Kr-85
1.8×10^{10} Bq ± 5%	5×10^{6} Bq	8.2×10^{8} Bq

metal atoms (FIMA) and 235 effective full power days (EFPD) operation (Table 2).

Objective of the test was to prove that all systems and the data acquisition work properly under hot conditions and to gain an initial experience of the KüFA operation. The heating program was divided into two phases—one phase at 1600°C for 5 h and a second phase at 1800°C for 5 h (see Fig. 4). Since burn-up, irradiation temperature, and fast fluence were relatively low and since this type of fuel was known to have excellent retention ability for fission products, no significant release of fission products was expected.

The Kr-85 release during the test was below the detection limit of the apparatus. In order to detect solid fission products, two cold plates were introduced and analyzed by gamma spectrometry after the test. Results could be obtained for Cs-137, but apparently there was a contamination of the cold plate container originating from the hot cell floor. After this test the procedure was changed by implementing the replacement of all containers after transferring the cold plates from the hot cell into a clean environment.

6.2 AVR 74/18. After the first heating test, a second AVR fuel element with a medium burn-up of 4.8% FIMA was heated in two phases up to 1600°C for 100 h and then up to 1800°C for 100 h. The heating program followed the full testing procedure including the reactor simulation at 1050°C for 10 h. From 1050°C the temperature was increased by 47°C/h to 1600°C according to the HTR Modul® accident simulations described in Sec. 2 (Table 3).

The Cs-137 inventory of AVR 74/18 at the beginning of the KüFA test was determined using gamma spectrometry. Cs-134 and Kr-85 activities could not be detected and were calculated using the INVENTAR Code from FzJ [9] (Table 4).

After the test a second gamma spectroscopy measurement was made, revealing no measurable difference in Cs-137 inventory between before and after testing (Table 5).

During the first phase the apparatus was shut down automatically. Graphite deposition on the cold plate surface caused the temperature of the cold finger to increase beyond safety limits. After the problem was found, the system was restarted. A second shut down happened at 1800°C. This time air bubbles inside the water cooling circuit caused the flow meter to indicate a zero flow of cooling water. The cooling circuit was de-aerated and water was refilled. The system could be restarted after a few minutes.

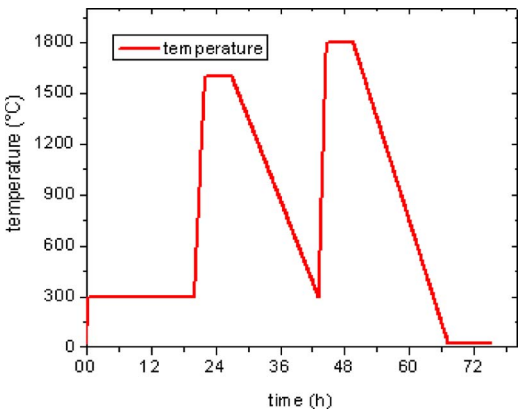

Fig. 4 Heating program for AVR 73/21

Table 3 Fuel element data for AVR 74/18

ID No.	AVR 74/18
Type	GLE-3
Graphite	A3-27
Fuel particles	16,400
Heavy metal	10 G
Fuel composition	UO_2
Enrichment	9.82% U-235
Burn-up	4.8% FIMA
Irradiation time	480 EFPD
End of irradiation	February 1985
Irradiation temperature	~700°C
Fluence	
Thermal	4.15×10^{21} cm^{-2}
>0.1 MeV	8×10^{20} cm^{-2}

According to earlier experiences with GLE-3 fuel in Jülich, a fractional release of Cs in the order of 10^{-6} to 10^{-5} and a fractional release in the order of 10^{-7} to 10^{-6} for Kr were expected.

As can be seen in Fig. 5, a slight release of Kr-85 could be detected—probably originating from matrix graphite grains. The release of Cs-137 increased following a typical curve during both heating phases up to 10^{-5} fractional release.

7 Heating Test HFR K6/3

The irradiation test HFR K6 was performed from 1990 to 1993 in the high flux reactor in Petten [4], in order to qualify the final fuel element design for the HTR Modul® reactor (proof test). The fuel element HFR K6/3 had a nominal burn-up of 9.7% FIMA and was irradiated for 633 EFPD. The fuel element data is given in Table 6.

The Cs-137 inventory at the beginning of the test was measured. The Cs-134 and Kr-85 activities were below the detection

Table 4 Fission product inventory of AVR 74/18 before test

Cs-137	Cs-134	Kr-85
3.4×10^{10} Bq ± 5%	1.8×10^{7} Bq	1.5×10^{9} Bq

Table 5 Fission product inventory of AVR 74/18 after test (corrected to beginning of test)

Cs-137	Cs-134	Kr-85
3.42×10^{10} Bq ± 5%	-	-

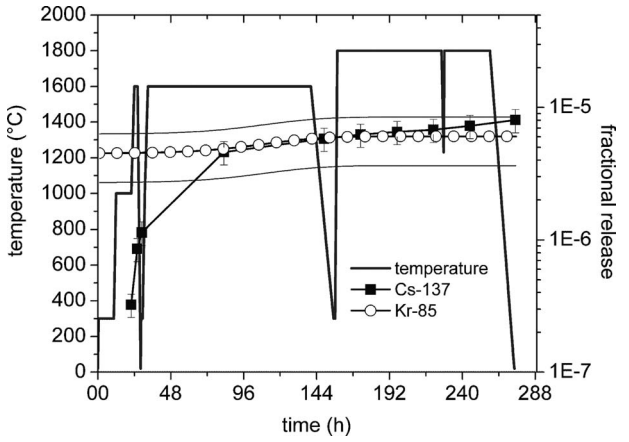

Fig. 5 Heating test AVR 74/18

Table 6 Fuel element data for HFR K6/3

ID No.	HFR K6/3
Type	GLE-4 similar
Graphite	A3-27
Fuel particles	14,600
Heavy metal	9.44 g
Fuel composition	UO_2
Enrichment	10.6% U-235
Burn-up	9.7% FIMA
Irradiation time	633 EFPD
End of irradiation	May 1993
Irradiation temperature	~1140°C
Fluence	
Thermal	2.5×10^{21} cm^{-2}
>0.1 MeV	4.8×10^{21} cm^{-2}

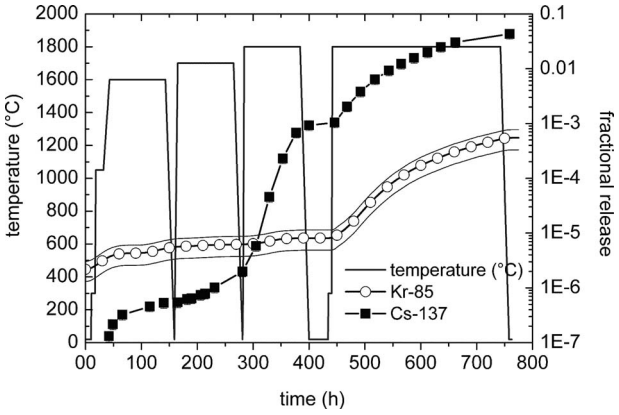

Fig. 7 Heating test HFR K6/3

limit and had to be calculated (see Table 7). Ag-110m and I-131 had completely decayed since the end of the irradiation.

The heating test of HFR K6/3 was performed in four phases. The first phase constituted 1600°C for 100 h, the second phase 1700°C for 100 h, and the third phase 1800°C for 100 h. After the third phase a fourth heating phase was performed at 1800°C for 300 h.

Until the end of the third phase (1800°C) only a slight increase in Kr-85 activity could be detected in the cold trap indicating that no particle had failed until that moment. After starting the fourth phase a sudden massive release of Kr-85 started, reaching 4×10^{-4} fractional release and indicating failure of several particles. Later postirradiation examination (PIE) using a scanning electron microscope (SEM) would verify this assumption (see Fig. 6).

Figure 7 illustrates the heating schedule and the measured release of Cs-137 and Kr-85. The Cs-137 release can be divided into two phases. Up to the end of the 1700°C (second heating phase) only small amounts of Cs-137 in the order of 10^{-6} are released. At 1800°C large releases start following a typical diffusion curve. In the end a fractional release of 3% was observed. It can be seen in Fig. 7 that the release curves of Kr-85 and Cs-137 follow the same shape in the fourth heating phase.

As a first conclusion it can be said that the fuel element HFR K6/3 showed an excellently coated particle performance with late particle failure at 1800°C and a low Cs release of up to 1700°C (10^{-6} fractional release). It is not clear whether the cooling and reheating of the sphere induced additional failures on the coated particles. However, such an effect would explain the sudden release of fission gas at the beginning of the fourth phase. It is assumed that the performed heating program represents a conservative case with respect to any possible accident scenario.

Table 7 Inventory of HFR K6/3 (beginning of test)

Cs-137	Cs-134	Kr-85
7.92×10^{10} Bq ± 5%	1.08×10^{9} Bq	4.32×10^{9} Bq

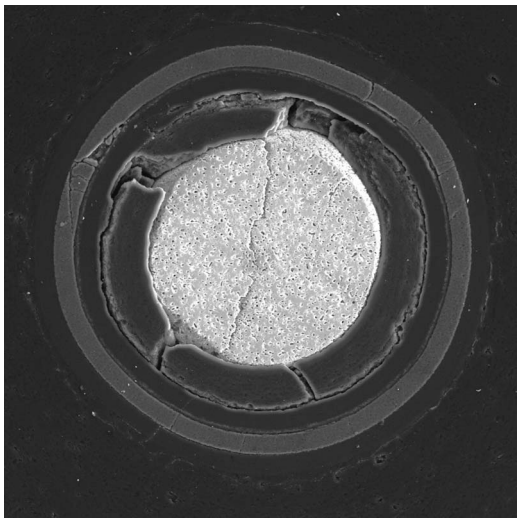

Fig. 6 SEM picture of a failed HFR K6/3 coated particle

8 Heating Test HFR K6/2

The irradiation test HFR K6 was performed from 1990–1993 in the high flux reactor in Petten [4], in order to qualify the final fuel element design for the HTR Modul® reactor. The fuel element HFR K6/2 had a nominal burn-up of 9.3% FIMA and was irradiated for 633 EFPD (Table 8).

The Cs-137 inventory at the beginning of the test was measured by gamma spectrometry. Again the Cs-134 and Kr-85 activities were below the detection limit and had to be calculated (see Table 9). Ag-110m and I-131 had completely decayed.

The heating test was performed in two phases (see Fig. 8). A first phase was performed at 1600°C for 100 h, and a second phase was performed at 1800°C for 200 h. After 45 h the system

Table 8 Fuel element data for HFR K6/2

ID No.	HFR K6/2
Type	GLE-4 similar
Graphite	A3-27
Fuel particles	14,600
Heavy metal	9.44 g
Fuel composition	UO_2
Enrichment	10.6% U-235
Burn-up	9.3% FIMA
Irradiation time	633 EFPD
End of irradiation	May 1993
Irradiation temperature	~1140°C
Fluence	
Thermal	2.5×10^{21} cm^{-2}
>0.1 MeV	4.6×10^{21} cm^{-2}

Table 9 Fission product inventory of HFR K6/2 before test

Cs-137	Cs-134	Kr-85
7.81×10^{10} Bq ± 5%	1.47×10^{9} Bq	4.29×10^{9} Bq

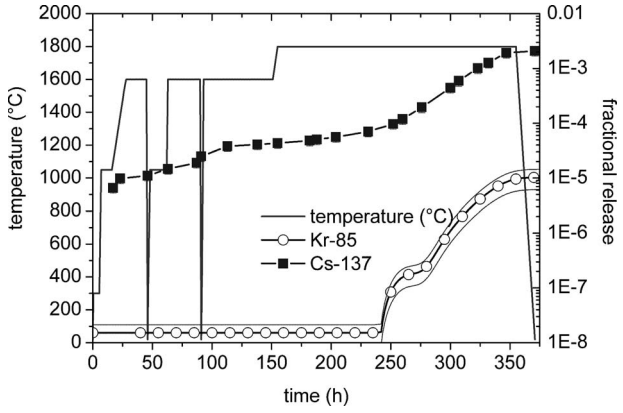

Fig. 8 Heating test HFR K6/2

was shut down automatically due to high cooling water temperature, and after 85 h the furnace was shut down due to a logic error.

During the first phase and the first 100 h of the second heating phase, no Kr-85 release could be detected. After 250 h increasing Kr-85 activity in the cold trap could be detected up to 10^{-7} fractional release. At 275 h a continuous ongoing release until the end of the test was observed. At the end of the test 10^{-5} fractional release was observed. Cs-137 was released continuously during the whole test up to 2×10^{-3} of fractional release. The release curves for Kr and Cs are given in Fig. 8.

After the test, the fuel element was measured again by gamma spectrometry in order to determine the amount of lost Cs-137, and no significant difference between the measurement before and after the test could be found [10].

9 Concluding Remarks

Existing equipment, developed in the Fz-Jülich and designed to perform the PIE of HTR-fuel elements, was upgraded and modified for installation in the hot cells of ITU in the framework of a shared cost action (SCA) of the European Commission. The hot installation has been completed, the system has been calibrated, and several heating tests on fuel elements have been performed and evaluated.

In this paper, the calibration of the fission gas measurement and the cold finger efficiency of KÜFA have been reported together with the results of the heating tests on AVR 73/21, AVR 74/18, HFR K6/2, and HFR K6/3 under hot conditions. The heating test on HFR K6/3 indicates an excellent behavior. The Cs-137 fractional release at 1600°C was determined to be less than 10^{-6} and even after 100 h more at 1700°C, the cumulated Cs release did not increase over the equivalent of one particle inventory. The fuel element HFR K6/2 showed a comparably high Cs release of 10^{-4} at 1600°C at the beginning of the test. This release probably originates from one or two defective particles that failed during irradiation. By 1800°C both fuel elements show a significant Cs-137 release of ~3% for K6/3 (after 400 h at 1800°C) and 2×10^{-3} for K6/2 (after 200 h at 1800°C). Increased release of Kr-85 at 1800°C indicates particle failure in both elements. Nevertheless, the performance is still very good considering this represents a very extreme accident (possible only in a large HTR). None of the other fission products could be measured by gamma spectroscopy.

Testing of fuel elements will be continued for confirmation and extension of these first results. In future tests the cold plates will be also analyzed for additional isotopes as Ag-110m and Sr-90. An electrochemical setup has been installed for the dissolution of the plate surfaces. The solutions will then be analyzed using mass spectrometry.

Acknowledgment

Part of this work was carried out under the Shared Cost Action Project HTR-F, HTR-F1, and RAPHAEL of the European Commission DG STD Fifth and Sixth Framework Programmes.

Nomenclature

Abbreviations

A-27 = fuel element graphite type
A-3 = fuel element graphite type
GLE = pressed fuel element with low enrichment
TRISO = tri-isotropic-coated particles (this refers to the 3 outer layers: inner pyrolytic carbon, SiC, and outer pyrolytic carbon and their isotropic nature—i.e., uniform properties in all three dimensions)
W/Rh = tungsten/rhenium high temperature thermocouple (up to 2500°C)

Symbols

A_{CT} = activity in cold trap (Bq)
$A_{G,0}$ = released activity from coated particle (Bq)
A_i = activity on cold plate i (Bq)
$A_{n,i}$ = introduced standard activity for calibration i (Bq)
C = average background (Bq)
D_{Kr} = diffusion coefficient of Kr in A-3 graphite
E_{KF} = cold finger efficiency
f_C = calibration factor
$\dot{I}$ = impulses per second
t_D = break through time (s)
T_G = furnace temperature (K)
T_U = environment temperature (K)
$\dot{V}_{He}$ = helium flow (l/h)
V_G = furnace volume (l)

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