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Control rod drive mechanism of nuclear power plant Krümmel/Germany. Copyright: Bernhard Ludewig.

G = German
E/G = English/German

The German Quiver Project

Quivers for Damaged and Non-Standard Fuel Rods

Sascha Bechtel, Wolfgang Faber, Hagen Höfer, Frank Jüttemann, Martin Kaplik, Michael Köbl, Bernhard Kühne and Marc Verwerft

1 Introduction and background of the German Quiver Project During the operational phase of a nuclear power plant, damaged fuel rods are usually collected separately in the spent fuel pool for a later disposal after the plant's final shut-down. In Germany the initially planned disposal path for damaged fuel rods was reprocessing. However, as part of the agreement on the first nuclear phase-out in 2000 in Germany ("Atomkonsens"), also transports of spent fuel to reprocessing plants were banned effective July 2005. With the first NPP to be shut-down in 2011 (KKI-1), its operator E.ON Kernkraft (EKK, now PreussenElektra) started a project in 2005 to establish a solution for the dry interim storage of their failed fuel rods in the on-site storage facilities, that had to be erected due to the end of reprocessing. Since the collected failed fuel rods were to be taken out of the pools only after the last regular fuel assemblies, a feasible storage solution for the failed fuel rods would have been needed by about 2016.

In 2006 EKK asked GNS Gesellschaft für Nuklear-Service mbH to join the project to ensure compatibility with the requirements of the transport and storage casks. By early 2007 two companies, one of them already Höfer & Bechtel, provided first design ideas and drawings. In 2009 the four German utilities jointly asked GNS to take over one of the concepts and develop it towards cask-licensing. In June 2010 this quiver solution was presented to Bundesanstalt für Materialforschung und -prüfung (BAM) to obtain a first authority feedback, in order to create a licensing documentation for transportation and storage.

After the political decision to again extend the operating times of the German NPPs later in 2010, the focus in the back-end activities of the utilities temporarily shifted to the regular cask licenses to ensure undisturbed operation by timely cask-loading campaigns. The first plant to be closed was still KKI-1, but now only in 2020. Hence the licensing of the quiver solution was temporarily suspended in favour of the ongoing licensing processes of transport and storage casks.

The second and final German phase out decision of June 2011 again revived the demand for a solution for failed fuel rods. Since the oldest plants, that had been taken off the grid only days after the Fukushima accident, were to remain shut down permanently, suddenly the development of a failed-fuel-rod solution was on a five-year time schedule.

As early as July 2011, the utilities asked GNS to resume the efforts with a special focus on the new time constraints. Regarding these new boundary conditions, GNS revised the requirements for such a quiver solution, now aiming at a very robust licensing concept as first priority, which was expected to reliably pass the licensing process faster than an economically optimized concept. During a workshop in August 2011 GNS and the utilities discussed this concept in detail and until November 2011 a specification was drafted. Based on that, five potential developers were invited to present their concepts in early 2012. Out of these five, the utilities finally agreed to adopt a hot-vacuum drying system with a quiver being able to accommodate several fuel rods as it was presented by Höfer & Bechtel. The quiver would regulatorily be treated as part of the cask and, to facilitate timely licensing, a cask-loading with only quivers was foreseen. In order to reduce the overall risk of the project, however, the utilities had also decided to pursue a second, different approach at the same time – hot-gas drying of individually capsuled fuel rods and assembling several capsules to a quasi-assembly – until the major challenges in the Höfer & Bechtel concept have been overcome.

At the time of the actual project start in mid-2012, there was very limited scientific information available on irradiated fuel rods containing water after a cladding perforation during operation occurred. EKK then decided to launch a research project with the Belgian nuclear research center SCK•CEN in Mol. As an additional partner SYNATOM, the company responsible for the front and the back end of the nuclear fuel cycle in Belgium, decided to join the so-called WETFUEL project. As will be described in more detail later, hydraulic properties were measured, proof of principle for temperature assisted vacuum drying was provided and finally water removal rates were determined. During this intensive research programme the overall concept could be validated and the industrial feasibility was shown.

Based on these results GNS in cooperation with Höfer & Bechtel developed two quivers for non standard fuel rods to fit into the basket slots of the existing cask types CASTOR® V/19 (PWR) and CASTOR® V/52 (BWR). The customizable internal baskets of the quivers facilitate the disposal of a large variety of nuclear inventory. Furthermore, the quiver features a robust design and a unique welded closure system, to provide a second cladding for the damaged fuel rods. This design and the accompanying dispatch equipment have been verified by a series of tests and qualification processes supervised by the German authorities, and have proven to be a reliable solution within the specified period of only five years.

The package design approvals for the quiver for CASTOR® V/19 and V/52 have been issued by the German authorities in 2017 and 2018, respectively. This first of its kind quiver solution is thus able to assure the dry interim storage of all non-standard fuel rods from the German NPPs in standard transport and storage casks.

In April 2018, the first three PWR-quivers were loaded at Unterweser NPP, while their final dispatch campaign including drying and welding was successfully carried out in October and November 2018. The next dispatch campaign has already started at Biblis NPP.

2 The Quiver – Design and function

The quiver for non standard fuel rods has been designed to be accommodated by the standard baskets of the CASTOR® V/19 or CASTOR® V/52.

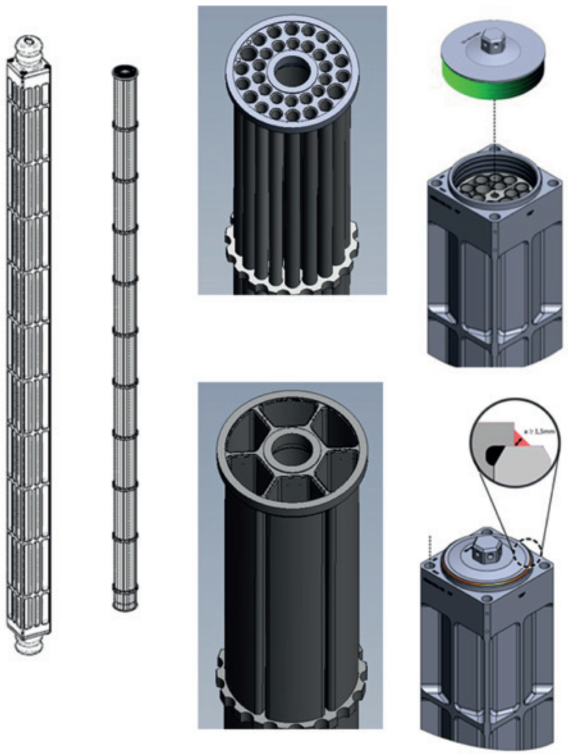

Fig. 1.
PWR-quiver with head- and foot-piece, inner basket, 32AR (upper-) and 6AR (lower picture), lid of BWR-quiver (upper-), welded lid (lower picture) – (from left to right).

The boundary conditions for the design of the quiver were:

- restoring the limited or missing barrier of the damaged fuel
- equivalence to the size and weight of standard fuel assemblies to fit into the CASTOR® baskets
- full compliance with CASTOR® license, regarding
  - criticality
  - dose rate
  - heat dissipation
- no negative impact especially on the CASTOR® lid system, regarding accident conditions
- ability to dry the fuel, that might be wet, due to cladding failure
- ability to get the license for processing the damaged fuel from the spent fuel pool to the loading of the final CASTOR®

The quiver (**Figure 1**) comprises the following parts:

- A forged stainless steel body with the central cavity to accommodate the inner basket. The body is made of one single piece, comparable to the body of the CASTOR®.
- The inner basket, which accommodates the damaged fuel rods or even parts of fuel rods and thus provides a defined and calculable geometry. Furthermore, the inner basket is designed to facilitate the drying of the damaged fuel. There are different types of inner baskets to accommodate even geometrically distorted fuel rods.
- A lid that is screwed into the top of the body, after the cavity and the fuel have been successfully dried. Additionally, the lid is welded to the body, to provide the gas tight barrier for the fuel.
- The head- and foot-pieces are designed as shock absorbers to limit the impact on the quiver itself and on CASTOR® lid in case of an accident. The head-piece also serves as load attachment point.

The inner basket of the PWR-quiver is licensed in two different variants. The most common type called 32AR features 32 tubes of three different diameters for fuel rods or encapsulated fuel rods of different diameters. The second type is called 6AR and is suited for geometrically distorted fuel rods. It is possible to load more than one fuel rod into one of the six tubes of the 6AR inner basket.

For the BWR-quiver three different types of inner baskets have been licensed. These are 18AR and 14AR for 18 resp. 14 fuel rods of different diameters as well as 8AR for geometrically distorted fuel rods. The 8AR can take up one or two fuel rods in each of its eight tubes.

Unlike a fuel assembly, which bends under mechanical loads, the quiver is a much more rigid and stiff structure. One of the biggest challenges was the design and qualification of the head- and foot-pieces regarding their shock absorber functionality to prevent additional stress to the CASTOR® lid system under accident conditions of transport.

To prove the effectiveness of the head- and foot-pieces, first the design was optimized using static loads of a hydraulic press with maximum force of 300 tons. Later on, the final design was proven in several drop tests. For that, the equipment for the drop tests was set up and qualified at the Höfer & Bechtel site at Mainhausen. All equipment for the drop tests of the 880 kg prototype quivers onto a rigid foundation was qualified in cooperation with BAM. Drop tests were performed at temperatures between -40°C (**Figure 2**) and +90°C (PWR) and -40°C to +110°C (BWR). The optimized design of the head- and foot-pieces was able to keep the maximum load to the quiver itself as well as the force on the lid system of the CASTOR® within the specified limits.

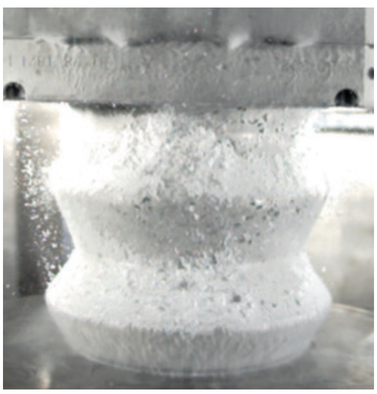

Fig. 2.
Drop test at -40°C, just before impact.

Manufacturing of the quivers and all of its components is performed under supervision of different authorities in order to assure quality specifications laid down in the license.

A second major challenge was the qualification of the drying process of the quiver cavity and even more so of potentially wet damaged fuel. Based on theoretical calculations and published experience with drying of damaged fuel, the drying concept was developed. Starting with a mock up for simulating a single damaged fuel rod up to the 1:1 original drying equipment, the qualification process for the drying was performed under supervision of BAM. The ability to monitor the drying process and to measure and verify dryness is as important as the drying process itself, as the test rods could be weighed and inspected for dryness, but the original damaged fuel rods can not.

Fruitful discussions with the experts of BAM led to the final design of the drying equipment and to the approved drying procedures. Participation in the international WETFUEL research program, which took place at SCK•CEN, Mol, Belgium, during the time of the development of the quiver drying system, was also a great opportunity to transform the experience from test rods to real fuel rods.

3 The Quiver as part of the CASTOR® Cask and its licensing implications

The disposal of spent nuclear fuel in Germany is essentially based on the established CASTOR® V casks. These casks consist of a thick-walled, monolithic cask body made of ductile cast iron with radial cooling fins, a basket for the spent fuel assemblies and an in-line double lid system. In case of CASTOR® V/19 for PWR-FA, the basket offers 19 positions while in case of CASTOR® V/52 for BWR-FA, the basket has 52 positions. **Figure 3** displays the design features using the example of CASTOR® V/52 in storage configuration.

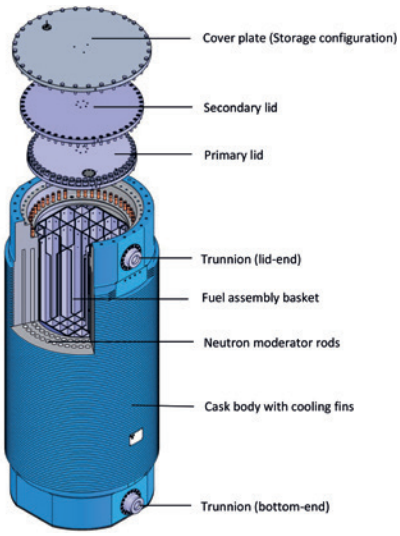

Fig. 3.
Design Features of the CASTOR® V/52 (Storage configuration).

In order to provide a comprehensive disposal concept also for damaged fuel rods, the quiver for damaged fuel rods had to be licensed as inventory for transport and storage in CASTOR® V casks. To achieve a straightforward and fast licensing process, the quiver was designed to be very robust and to comply with the existing boundary conditions of the CASTOR® V cask:

- equivalence of size and weight of standard fuel assemblies to fit into the CASTOR® baskets
- no negative impact on the cask, especially on the CASTOR® lid system under accident conditions
- ability to dry the damaged fuel rods to an extent, that no extra measures in the cask or quiver design are necessary.

The licensing approach was further optimized regarding the situation of shut-down NPPs with the need for a fast track disposal concept for a complete removal of nuclear fuel from their spent fuel pools. This led to a two-step approach:

1. Fast track concept featuring:
   - Robust quiver design with significant safety margins
   - Conservative cask loading pattern (quiver only)
   - Safety report with very conservative boundary conditions
   - Substantial experimental tests to accelerate the safety evaluation process
2. Optimized concept featuring:
   - Robust quiver design with higher load capacity
   - Optimized cask loading patterns (quiver and spent fuel assemblies)
   - Safety report with adequate boundary conditions

The first approach proved successful: The first transport license for the leading PWR-quiver in CASTOR® V/19 casks was granted on schedule in April 2017, subsequently the first storage license for Biblis NPP in June 2018. The transport license for the BWR-quiver in CASTOR® V/52 casks was granted in April 2018, the first storage license for Krümmel NPP in December 2018.

In order to economically optimize the use of the quiver system, GNS works on improving the capacity of the quivers and enabling also mixed cask loadings with both quivers and regular fuel assemblies. First feasibility studies have been started.

4 Quiver handling and service equipment

The quiver project is divided into three subprojects. One of these subprojects was the development and manufacturing of equipment for handling and preparation of damaged fuel rods for the loading into the quivers.

4.1 First step: Loading of damaged spent fuel into the Quiver

Using trusted under water handling tools the damaged fuel rods are loaded under water into the quivers. This process is schematically shown in **Figure 4** left.

For the loading of the fuel rods with minor damages (e.g. gastight with reduced cladding thickness or gastight with deformations) the fuel rod is gripped at its upper pin by means of a plier. The operator lifts the tool with the crane and positions the attached fuel rod above the quiver. Subsequently, the fuel rod is lowered into a free loading position of the internal basket of the quiver. Examples of customized internal baskets for different kinds of damaged fuel rods are shown in **Figure 4** right.

Before loading into the quiver, heavily damaged fuel rods or even fuel rod sections down to the size of pellets, are placed in small handling tubes. The handling tubes are handled with a dedicated gripper (**Figure 5**).

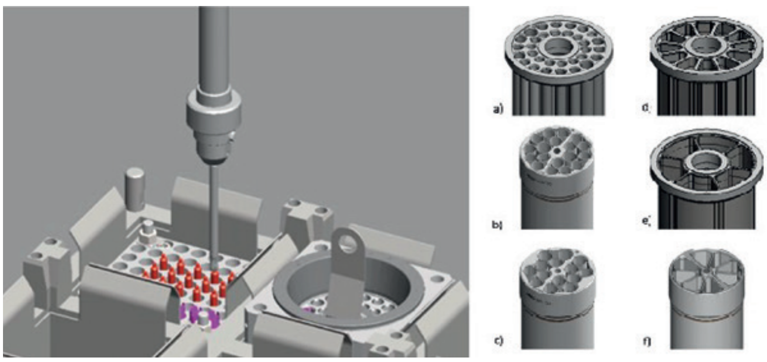

Fig. 4.
Damaged fuel rods and handling tubes with fuel rod sections are placed in a receptacle, which is positioned in the fuel assembly storage rack. Next to that the quiver is waiting for the loading (left). Different internal baskets for varying kinds of bent damaged fuel rods (right).

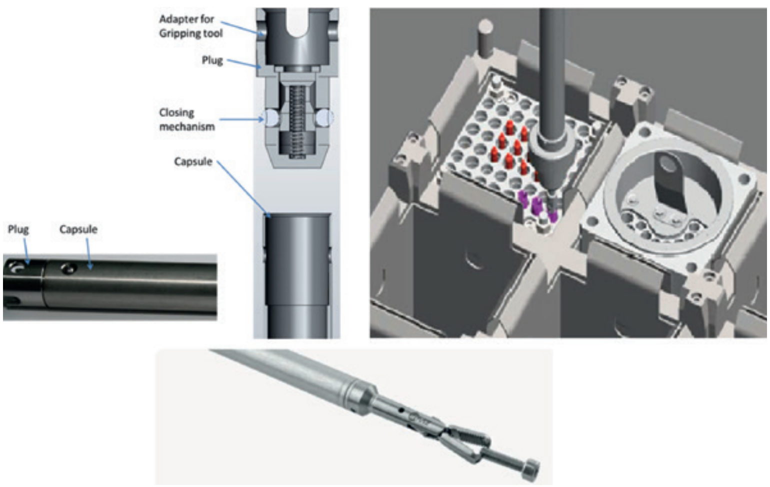

Fig. 5.
Handling tube for the collection of heavily damaged fuel rods, smaller sections of fuel rods or even broken pieces down to the size of pellets (left). In analogy to the loading of fuel rods with an intact upper pin, the handling tubes are placed in the internal basket of the quiver (right). Example for a gripper to collect fuel debris for placement in cartridges before loading into the quiver (bottom).

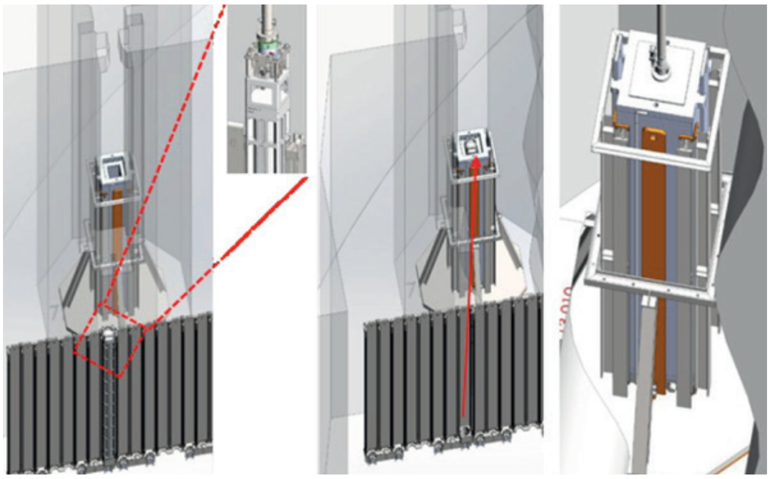

Fig. 6.
The quiver is still placed in the fuel-assembly rack with the transfer-head piece already attached. The primary shielding is inside the loading station at the usual loading position of the CASTOR® V cask (left). The quiver is lifted out of the rack and positioned inside the primary shielding (center). After removal of the transfer-head piece the primary shielding is closed with a top shielding. Now the shielding basket is ready to be lifted out of the pool and handled on the reactor floor (right).

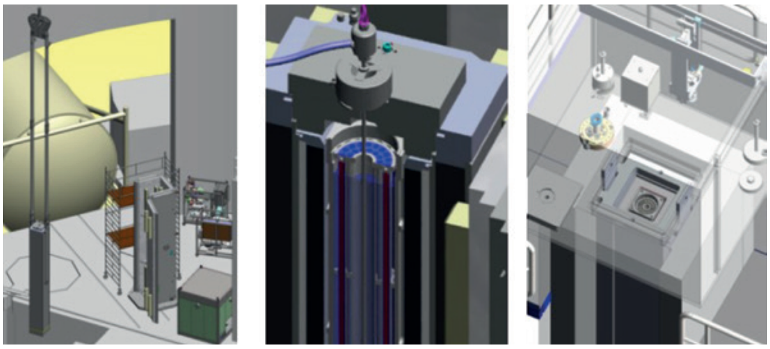

Fig. 7.
The quiver inside the primary shielding is lifted out of the pool and into the handling station on the reactor floor (left). Dewatering of the quiver inside the handling station (center). View into the mobile hot cell on top of the handling station (right).

The actual process of loading the handling tubes into the internal basket of the quiver remains unchanged compared to the fuel rods with minor damages, which are directly loaded into the quiver.

4.2 Second step: Dispatch of the Quiver

In contrast to the regular dispatch of spent fuel assemblies under water in the spent fuel pool, the dispatch of the quiver is performed outside the spent fuel pool on the reactor floor. This approach is motivated by the possibility to use much simpler technology than would be required for underwater processing in the spent fuel pool. This also yields an increase in process stability. However, this approach requires some additional equipment especially with regard to shielding.

After loading of the quiver with damaged fuel rods a transfer-head piece is attached to the top of the quiver for handling purposes. This transfer-head piece allows the handling of the quiver like a standard fuel assembly with a gripper. The quiver is lifted out of the storage rack and is placed into a shielding basket on the bottom of the pool. The shielding basket is the primary shielding of the quiver during handling outside of the spent fuel pool. In the pool it is positioned in a loading station waiting to take up the quiver. As shown in **Figure 6** the loading station is located at the position in the spent fuel pool, where the CASTOR® V casks are usually loaded during a standard defueling campaign. It consists of a stable base plate with welded lateral guide and support elements for the shielding basket. The loading station and the shielding basket are handled with the same crane system of the NPP.

After transferring the quiver into the shielding basket, the transfer-head piece is removed and a top shielding, closing the top of the shielding basket is attached to the primary shielding. The shielding basket including the quiver is now lifted out of the pool and positioned into a handling station on the reactor floor (**Figure 7**).

The handling station is where the actual dispatch of the quiver takes place. It consists of a secondary shielding system, an operating platform and a mobile hot cell, which is operated by remote control. The shielding block as the secondary shielding system for the quiver consists of a sandwich structure of polyethylene and steel. One side can be opened for placing the shielding basket with the traverse into the shielding block. An operation platform is fitted to the shielding block, enabling access to the upper part of the shielding block and for inspection works. Inside the mobile hot cell the drying and welding of the quiver is performed. The mobile hot cell provides a barrier between the damaged fuel rods in the quiver and the atmosphere of the controlled area in the NPP, retaining particles etc. The atmosphere inside the mobile hot cell is monitored and can be replaced with an inert gas atmosphere. The exhaust line from the mobile hot cell is connected to the building ventilation system via a particle filter, providing further contamination control.

Now the dewatering and drying of the quiver can take place. While the dewatering is performed by suction of the water the drying process is more sophisticated: while the quiver is heated to temperatures above the boiling point of water by hot air from a heating unit, a vacuum drying device operates using a special throughput of hot air, utilizing humidity sensors to monitor the residual moisture in the quiver and its inventory.

After drying, the quiver is filled with helium for helium leak testing and to provide inert conditions. The lid of the quiver is screwed in using remote manipulation tools. In order to provide the gas tightness of the quiver, a welding seam is produced by means of a remote welding machine. The welding process had to be qualified by the German authorities and it was shown that the automated process generates a gastight welding seam fulfilling the design specifications. Finally, after the welding a leak tightness test of the welding seam is performed inside the mobile hot cell.

As mentioned above, all the operations inside the mobile hot cell are performed by remote control and are monitored by video. This significantly reduces the radiation exposure of the personnel. **Figure 8** shows the

Fig. 8.
The remote controlled handling device inside the mobile hot cell with one of the six cameras inside the cell (top, left). The remote control terminal which is placed next to the handling station (top, right). The remote controlled automatic welding device (bottom).

manipulation device and one of the six cameras inside the mobile hot cell. The remote control station is positioned beside the handling station and is connected to the mobile hot cell.

After the dispatch, the quiver – still inside the primary shielding – is transferred back to the loading station in the pool. Here the quiver is lifted out of the shielding and put back into the storage rack, where it remains until being loaded into the CASTOR® cask.

5 Drying spent nuclear fuel

5.1 Boundary conditions for drying fuel

Both the defining criteria of damaged fuel and the procedures for handling damaged spent nuclear fuel vary from country to country depending on the regulatory requirements *[1]*. For intact fuel assemblies, the transfer from wet to dry storage goes generally without problems as the intact cladding of the fuel rods ensures that all water is "easily accessible". For non-intact fuel rods, one may expect that the inner parts of the rod such as the plenum, fuel-cladding gap, cracks and fissures in the UO_2, pellet-pellet dishes etc. are partially or completely filled with water. Extraction of the water that has seeped into the fuel may be difficult. As-fabricated fuel rods have a fuel-cladding gap of several tens of micrometers, but progressively, the cladding creeps towards the fuel while the fuel undergoes thermal expansion and swells due to fission product accumulation and after a certain period of time, the fuel-cladding gap is closed in hot operating conditions. In cold stage, the gap re-opens due to the larger thermal contraction of the fuel, but the gap size of spent fuel is much smaller than the as-fabricated gap. Already for non-failed fuels, the gas connectivity in an irradiated fuel rod is a complex phenomenon to describe quantitatively. Upon cladding breach, the fuel rod internals are exposed to the primary coolant and later to the spent fuel pool water. After cladding breach, e.g. as a result of debris fretting causing a pinhole defect, secondary cladding defects rapidly develop due to hydrogen uptake by the Zircaloy cladding *[2, 3]*. Furthermore, UO_2 potentially oxidizes to higher oxides upon exposure to oxidizing conditions ($UO_2 \rightarrow UO_{2+x} \rightarrow U_4O_9 \rightarrow U_3O_7 \rightarrow U_3O_8$). Compared to UO_2, the higher oxides which essentially keep the fluorite arrangement of the parent UO_2 structure (UO_{2+x}, U_4O_9 and U_3O_7) show a net contraction of their structure *[4-6]*, but when the U_3O_8 phase forms, a huge expansion (36 %) occurs *[7]*. For non-intact fuel, one must thus take into account that water has interacted with the UO_2 fuel, and that hydriding and inner wall oxidation of zircaloy cladding may have occurred, which further complicates a theoretical prediction of water removal kinetics.

5.2 Hot laboratory drying tests of real spent nuclear fuel segments (WETFUEL Project)

In order to reduce the uncertainties of water removal rates from damaged irradiated spent fuel rods, an experimental setup was developed to perform wetting and drying tests under well-controlled conditions. The setup further allowed to measure the hydraulic resistance for gas flow as well as the removal rate of water through a spent fuel segment of variable length. The device consisted of two instrumented vessels holding a fuel rod segment in between them, sealed in such a way that any water, gas or vapor flow had to pass through the clamped fuel rod segment (**Figure 9**).

Spent fuel samples were taken from a failed fuel rod and from a nearly identical unfailed fuel rod with a rod average burnup around 50 GWd/tHM irradiated in the Belgian Tihange 1 PWR. Tested fuel samples showed the typical crack pattern for irradiated nuclear fuel (**Figure 10**). For analytical studies, fuel rod segments of various lengths were investigated. In this article the results obtained from two segments of 50 cm and one of 10 cm length are discussed.

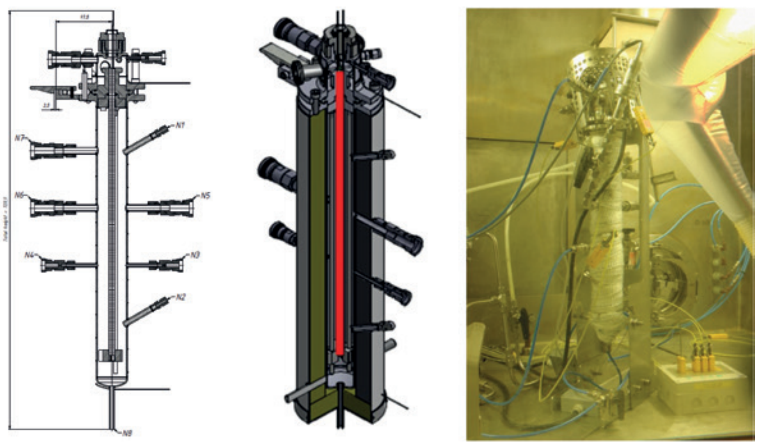

Fig. 9.
Hot-cell installation for wetting and drying experiments on spent nuclear fuel segments: Design drawing of the two vessels: a large bottom vessel and a much smaller top vessel (left). 3D cutout view of the equipment with schematic indication of a mounted spent fuel segment (center). View of the equipment installed in hot-cell (right).

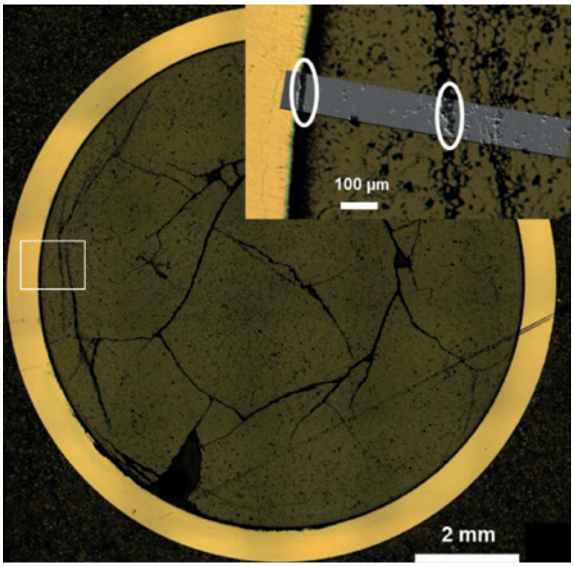

Fig. 10.
Cross section of the spent fuel segment WET1, taken from the failed fuel. The cracks and gap do not show any particular severe degradation. The missing part on the bottom side is caused by sample preparation. Inset: detail of the gap region, with an overlay of a Scanning Electron Microscopy (SEM) image. The greater depth of view of the SEM allows one to better assess the width of irregular areas such as cracks and the pellet-clad gap than observations made from optical micrographs.

Prior to tests on real spent fuel rod segments, mock-up tests were performed with a segment filled with fine Al_2O_3 powder and sealed on both ends with a porous filter plug.

The test setup allowed various types of tests:

- Hydraulic resistance for dry gas flow
- Wetting-Drying sequence
- Water pocket drying

The hydraulic resistance can be derived by measuring a gas flow at constant pressure difference, which works well for low hydraulic resistance samples, or by measuring the rate of pressure change in either of the two vessels as a function of pressure difference over the sample, which proved to be more accurate for samples with high hydraulic resistance. Under conditions of laminar flow, the molar flow rate $Q_m(t)$ is equal to:

$$Q_m(t) = \frac{M}{R\,T}\,V_1\,\frac{d}{dt}\big(P_1(t)\big) = \frac{M}{R\,T}\,\frac{\pi\,r^4\,(P_2(t)^2 - P_1(t)^2)}{16\,\eta(T)\,L} \qquad (1)$$

where $Q_m(t)$ is the instantaneous mass flow rate (expressed in $g.s^1$) through the segment, $P_1(t)$ and $P_2(t)$ are the top and bottom pressures as a function of time, V_1 is the volume of the top vessel, r is the radius for an effective capillary for the gas flow path, $\eta(T)$ is the dynamic viscosity of a certain gas at temperature T (e.g. Ar, air or H_2O), M is the molar mass of the considered gas, L is the flow path length, R is the universal gas constant. From (Eq. 1), the effective hydraulic radius can be readily calculated (see also column 3 of **Table 1**:

$$r = \sqrt[4]{\frac{16\,\eta(T)\,L\,Q_m(t)}{\pi\,(P_2(t)^2 - P_1(t)^2)}\,\frac{R\,T}{M}} \qquad (2)$$

A complete wetting and drying sequence consisted of inserting an excess amount of water in the lower vessel such that the lower part of the fuel rod segment would be completely immersed. The gas cushion above the water was then pressurized such that the sample segment was progressively filled with water until the moisture readout in the top vessel indicated the presence of liquid water i.e. full percolation did occur. The system was then soaked for a minimum period of 2 hours to allow finer cracks and gaps to be wetted as well. The lower vessel was then drained and both top and bottom vessels were heated to a preset temperature while being pumped. During the pumping sequence, the pressure was monitored as well as the moisture content in the exhaust line. After reaching pressures below 1 mbar in both top and bottom vessel, a pressure rebound test was performed *[8]*. To this end, the exhaust lines were shut and the pressure increment was monitored for 30 minutes. If the pressure would not exceed 4 mbar, the test was considered complete. The drying sequence, plotted in **Figure 11**, clearly showed several phases: in a first phase, the pressure rapidly dropped until ~10 mbar, at which point the pressure stabilized while liquid water was slowly removed from the fuel column. The humidity in the exhaust lines remained elevated (dew point between 10 °C and 20 °C). Once the liquid water was removed from the segment, the pressure and humidity further dropped. Considering the performance of the pumping system, the vacuum was expected to asymptotically approach ~0.5 mbar. In the example shown in Figure 11, the first pressure rebound test was nearly successful after around 6 h. Upon further drying, the pressure and humidity gradually evolved to 0.3 - 0.4 mbar and 40 °C. A successful dryness test was performed after 24 h. Further drying did not result in any significant changes in vessel pressure or relative humidity of the exhaust gas. The test was concluded after 96 h with a third dryness test, which was again successful.

The wetting and drying sequence yielded a successful demonstration of the feasibility of the drying principle but was difficult to quantify. Quantification of water removal rates was approached by two methods. At first, the hydraulic resistance of a fuel rod segment was assessed under dry conditions (see above), and in a second stage, "water pocket tests" were performed at different temperatures. To this end, 10 ml of water was poured into the top vessel which was then sealed, the whole system was heated and pumping was performed from the bottom vessel. Depending on the drying temperature, the drying time was shorter or longer and correspondingly, the lower vessel pressure was at a higher or lower equilibrium during the drying process: ~4 mbar for 3 h when drying at 130 °C and at ~2.5 mbar for more than twelve hours when drying at 110 °C.

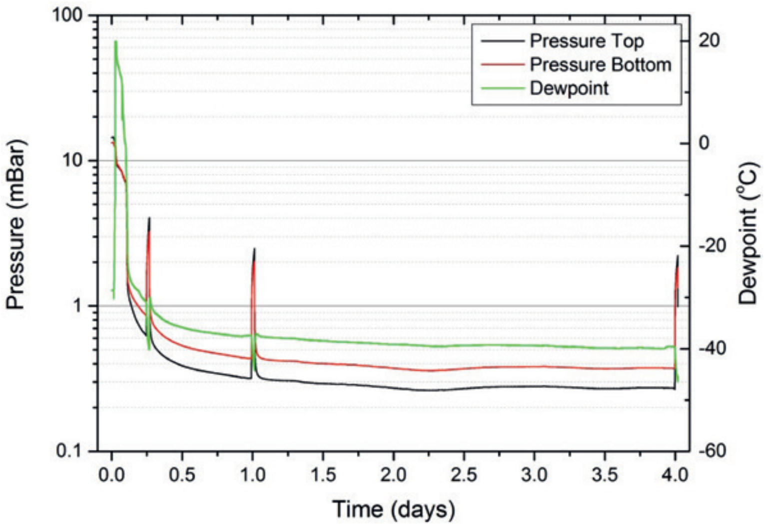

Fig. 11.
Drying sequence with monitoring of pressure evolution in both top and bottom vessel and evolution of the pressure during a 30 minutes dryness test, performed after approximately 6 h of drying, 24 h and 96 h.

Sample ID	Length	Effective hydraulic radius	Water removal rate (g/day)		
			110 °C	120 °C	130 °C
WET1	50 cm	89 ± 2 µm	15 ± 2	28 ± 2	44 ± 5
WET2	50 cm	103 ± 2 µm	33 ± 4	63 ± 7	89 ± 10
WET3	10 cm	85 ± 1 µm	73 ± 8	133 ± 15	207 ± 23
WET5b	17 cm	102 ± 2 µm	90 ± 10	164 ± 18	321 ± 36

Tab. 1.
Hydraulic radius of different samples.

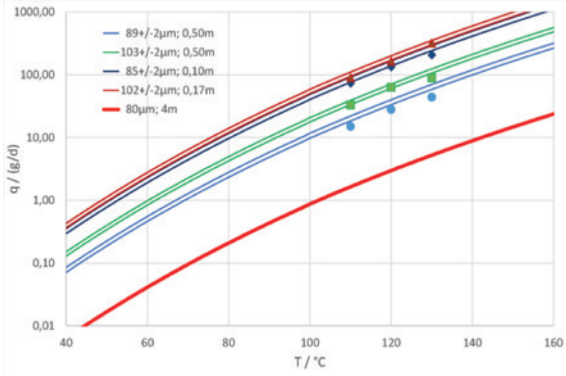

Fig. 12.
Vapor mass flow rates determined directly for different segments (symbols) and calculated on the basis of dry hydraulic resistance measurement (thin solid lines).A calculated release rate for a 4 m long rod with a hypothetical 80 µm hydraulic radius is also calculated (thick red line).

From the same water pocket drying experiments, vapor flow rates can be determined by shortly closing the valves of the bottom chamber and monitoring the instantaneous pressure increment (see Eq. (1)). Once the macroscopic amounts of water were removed from the top vessel in a water pocket test, the pressure in the top vessel dropped and the system evolved to an apparently dry state. Although both pressure and relative humidity indicated that the system reached near perfect dryness, further tests indicated that the top vessel continued to contain a minute amount of water vapor at a pressure of about 60 mbar that could not escape through the fuel rod. This can be interpreted as leaving the laminar flow regime, for which the Knudsen number (*Kn*, i.e. the ratio of gas mean free path $\bar{l}$ to the lateral dimension w of the flow path) is less than 0.01.

$$Kn = \frac{\bar{l}}{w} \qquad (3)$$

The mean free path is proportional to the temperature and inversely proportional to the pressure (see e.g. *[9]*):

$$\bar{l} = \frac{k_B}{\sqrt{2}\pi d^2}\,\frac{T}{P} \qquad (4)$$

Herein, k_B is Boltzman's constant, *T* the absolute temperature, expressed in Kelvin, *P* the pressure, expressed in Pa and *d* the diameter of the gas molecules (d = 0.4 nm for H_2O). With a vapor pressure of 60 mbar (6,000 Pa) at 120 °C (393 K) and typical crack width of 15 µm the Knudsen number is *Kn* = 0.09, well in the transition regime to molecular flow. Within that flow regime, mass-flow is considerably lower and vapor-removal effectively stops.

Mass flow rates were calculated from the hydraulic radius as derived from the dry hydraulic resistance measurements (**Figure 12** and **Table 1**). The excellent agreement between the different water removal approaches provided a sound scientific basis, allowing quantitative assessment of drying times, thus substantially reducing risks for the utilities. Furthermore, the amount of residual water not accessible with the technique of hot-vacuum drying can be quantified, showing a huge margin to design assumptions.

6 The first Quiver Campaign and outlook on the industrial use

6.1 Preparation and cold trial at Unterweser NPP

Before the very first dispatch campaign at Unterweser NPP could start in October 2018, an extended work program had to be successfully completed. This comprised the loading of the damaged fuel rods into the quivers as well as the installation and site acceptance testing of the complete dispatch equipment (**Figure 13**).

The loading of the PWR quivers (**Figure 14**) with the fuel rods was carried out according to a clearly defined loading plan. Each loading step was precisely documented.

Before the dispatch campaign, the equipment had to be set up in the reactor building, where the site acceptance test was carried out. In addition, various supporting documents were submitted to the supervisory authority for approval. In order to prove that the welding equipment was set up correctly and in accordance with the requirements, a trial weld was carried out prior to the actual campaign.

6.2 First Quiver Campaign – Sequence of Handling and Service Activities

As described in chapter 4, the handling of the quivers takes place at two different levels inside the containment: The loading station is positioned in the spent fuel pool, while the

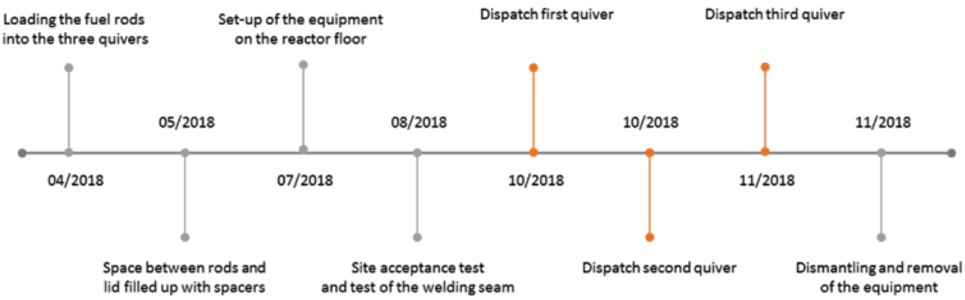

Fig. 13.
Preparation, cold trial and dispatch at Unterweser NPP.

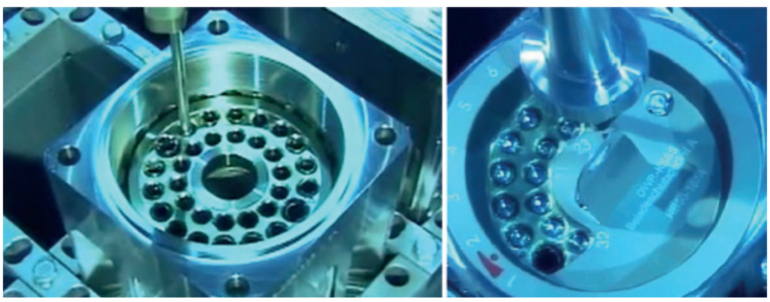

Fig. 14.
Measuring the length for the spacers (left), insertion of the spacers into the quiver (right).

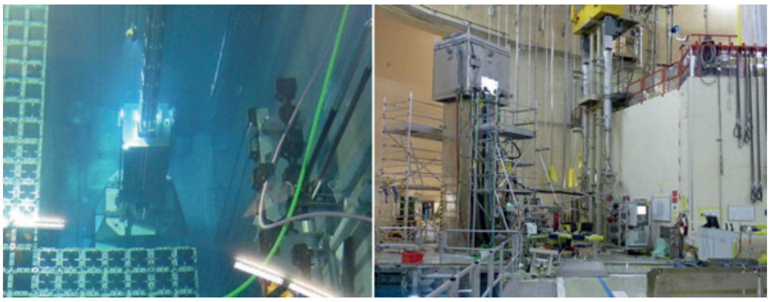

Fig. 15.
Shielding basket and loading station in the spent fuel pool (left) and the service station with mobile hot cell positioned on the shielding block and equipment on the reactor floor (right).

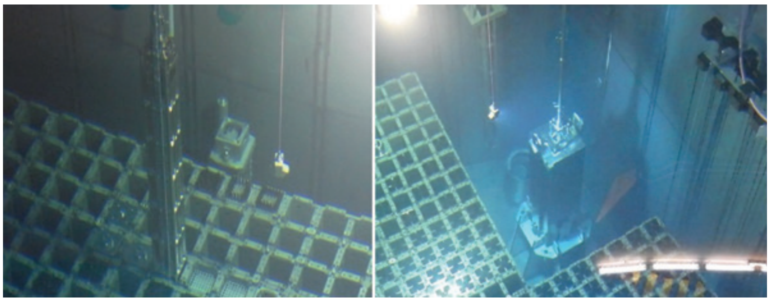

Fig. 16.
Storage rack and quiver (left), top shielding on shielding basket (right).

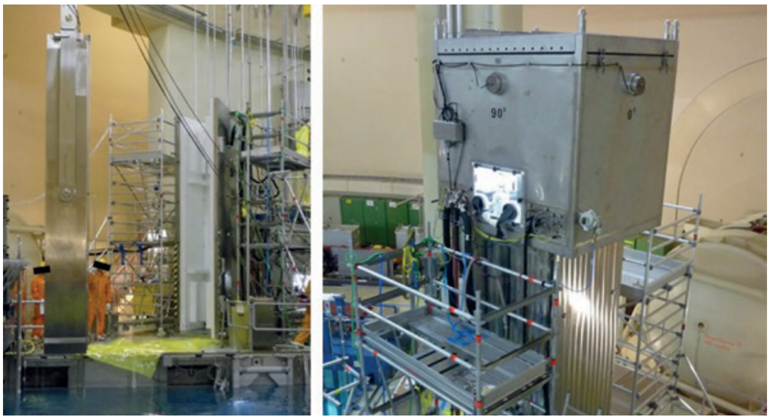

Fig. 17.
Transport of the shielding basket to the shielding block (left), mobile hot cell (right).

Fig. 18.
Close-up of the lid screwing device (left), welding machine and lid screwing device (right).

Fig. 19.
Welding device (left), welded lid (right).

service station is located at the reactor floor outside of the pool (**Figure 15**).

After mounting the transfer head piece, the loaded quivers were lifted up out of the storage rack and transferred to the loading station into the shielding basket. Here the head piece was removed and a top shielding was installed to close the shielding basket (**Figure 16**).

The shielding basket containing the loaded quiver was then lifted up to the reactor floor. Once the shielding basket is inside of the shielding block, in a first step the quiver was dewatered. Next, the mobile hot cell was mounted on top of the shielding block (**Figure 17**). Prior to drying the quiver, the top shielding was replaced with the multi cover, which provides connections to the drying device and the heating device.

The quiver was then evacuated using vacuum pumps, the humidity was removed from the quiver and was recovered as condensate in a condenser. The operating data of the drying device were recorded and stored in a stationary computer. After finishing the drying procedure, the interior of the quiver was filled with helium.

Next, the lid screwing device (**Figure 18**) was positioned on the base body of the quiver. It screws the lid into the base body automatically, while all the parameters can be monitored remotely by the operator.

Afterwards the welding machine was positioned, that automatically connected the lid and the base body of the quiver by means of a qualified welding procedure (**Figure 19**). As last step, the leak tightness of the welding seam was tested.

Finally, the quiver could be transferred back to the storage rack in the spent fuel pool.

6.3 First Quiver campaign – Main results

The dispatch of the first quiver started in Unterweser NPP on 12 October and was completed on 21 October 2018. The drying process lasted about 6 days. The maximum dose rate at the service station was less than 70 µSv/h. The second quiver dispatch started on 23 October and was completed on 01 November 2018. Again the drying process lasted 6 days. The third dispatch started on 02 November and lasted until 16 November. The drying process took about 11 days. The dose rate of the second and the third dispatch were comparable to the first dispatch.

The major results of the first three dispatch cycles are:

- The qualified processes for handling, drying and welding are robust and reliable.
- The "out of pool"-handling results in very low radiation exposures for the service personnel.
- It has been shown that it is feasible, to dry damaged fuel in an industrial process on site.

6.4 Outlook on the upcoming Quiver Campaigns at Biblis and Krümmel NPP

Meanwhile, the second PWR quiver campaign has already started at Biblis NPP, comprising 9 PWR quivers. After installation of the handling and service equipment, the test of the welding device by a trial weld was completed in December 2018. The actual campaign has started in January 2019 and the first quiver was dispatched by January 20th.

The first BWR quiver campaign is planned at Krümmel NPP. The storage license has already been granted. Currently the preparations are mainly focused on the required documents. The campaign is scheduled for summer 2019 and will comprise 9 BWR quivers.

With the Krümmel campaign, the GNS quiver system will provide conclusive proof, that it can be used industrially for failed fuel rods both from PWR- as well as from BWR reactors.

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