

EXPERIMENTAL SETUP FOR HYDRAULIC RESISTANCE MEASUREMENTS ON SPENT NUCLEAR FUEL

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ABSTRACT

A laboratory scale hot cell installation was developed for studying challenges in conditioning leaking spent fuel for safe mid-term dry storage. Regardless of the drying approach of spent fuel, axial gas flow through the fuel column is the most important physical fuel property, and it also links directly to various safety aspects, such as fuel behaviour in loss of coolant accident (LOCA). The installation was developed to measure the hydraulic resistance in spent fuel column, for both intact and non-intact, using argon, helium and water vapour. The design took into account several limitations of hot cell environment, such as small dimensions, manipulator operations, degradation of components under radiation, and overall safety issues.

1. Introduction

The protocols and procedures for handling spent damaged nuclear fuel vary within the IAEA countries [1]. The main common goal of these procedures is to ensure that spent fuel can be safely stored. In general, spent fuel is cooled down in storage pools located at the proximity of the nuclear power plants. After dissipation of the decay heat in storage pools, many concepts rely on mid-term dry storage of spent fuel prior its final disposal. For intact fuel, the transfer from wet to dry storage is generally without problems as the intact cladding ensures that all water is “easily accessible”. For non-intact fuel, the drying procedures prior to mid-term dry storage must take into account that water has interacted with the UO₂ fuel, leading to unwanted effects and thus possibly more complicated kinetics of water removal. Regardless of the drying process, hydraulic properties in the fuel axial direction have a major influence on the vapour transport during drying. Axial gas flow in fuel rods is also highly relevant for various accident scenarios, such as ballooning and burst occurring in a loss of coolant accident (LOCA). Accurate knowledge on axial gas flow is thus required for analysing and understanding fuel behaviour in reactor transient accidents.

Motivated by the above, a laboratory scale hot cell installation was designed and constructed at SCK•CEN. The installation consisted of two independent compartments, between which an open-ended fuel segment up to 500 mm could be installed and tested. Both compartments were equipped with gas supplies and pressure meters, inlets allowing experiments with dry gas, with water and water vapour at temperatures between room temperature and 150 °C. This

paper describes the main technical decisions which were made during the development and the limitations that had to be overcome due to the hot cell environment.

In the present paper, we report on the operation principles, design choices and operational experience. The performance of the instrument on gas flow measurements through a spent fuel segment is also presented. The results obtained for the wetting and drying itself will be presented elsewhere.

2. Design and development

The installation was designed and developed to provide a proof-of-principle for various drying protocols for non-intact spent fuel prior to mid-term dry storage, and to study axial gas flow in a spent fuel column. Before the development of the device could start some parameters and criteria had to be set. First, the drying protocols to be investigated were chosen. Then, a compromise between the optimal parameters for the protocols and hot cell limitations was made. The criteria for the installation converged to the following.

- Spent fuel segment:
 - Maximum length: 500 mm
 - Minimum length: 75 mm
 - Open on both ends
- Gases used in the experiment:
 - Ar, He
 - Water vapour
- Measurement capabilities:
 - High pressure 0 bar – 3 bar absolute
 - Low pressure 0.01 mbar - 500 mbar.
 - Dew point -50 to +20 °C.
 - Agilent data-recording for 12 parameters simultaneously
 - Measurement interval from 1 to 10 s.
 - Presence of water: conductivity probe
 - Operation temperature: room temperature to 150 °C
- Hot cell limitations:
 - Maximum of 4 bar overpressure in the flask
 - Maximum outer surface temperature of the flask: 80 °C
 - Contamination control in gas outlet cold trap

The installation consists of a main body, called flask, which holds the fuel rod segment, Figure 1. The flask contains inlets and outlets for gases and water, and heating elements and thermocouples for accurate temperature control. The flask itself is divided in two compartments: a larger lower reservoir and a smaller upper reservoir, separated by a leak-tight seal, which is only penetrated by the fuel rod segment which is open-ended on both sides. Gas connection between the lower and upper reservoir is only possible through the fuel column itself. Two peripheral systems are operated for accurately setting up the desired conditions; the inlets for water and gas and the outlets connected to a vacuum system. A schematic view of the installation is given in Figure 2.

3. Instrumentation and safety issues

The installation was developed to work under the conditions listed above. The parts were fabricated and assembled in-house at SCK•CEN. The reservoirs were designed to withstand

4 bar overpressure and the relief valves were set at 3.5 bar to allow for adequate operational margin to the operational range (0-3 bar). Underneath the alpha-box, a vacuum and valve system with a dew point measurement and cold trap were located. Gamma monitoring was inserted in the cold trap to follow possible contamination build-up during the experiments. The vacuum system consisted of a rotary vane pump with a gas ballast, an active carbon filter and a condense separator. The inlet tubing for the pump had a mesh filter to trap particles and protect the pump. The exhaust of the vacuum pump was directed back into the hot cell and removed via the hot cell ventilation.

For the valve system, the 210 series' solenoid valves from ASCO were used. These valves could be switched to bypass the cold trap, the dew point measurement, and the vacuum pump according to the desired experiment scenario. In case of a power loss, the valves in between the equipment were set to close and the bypasses were set to open to prevent any pressure rise.

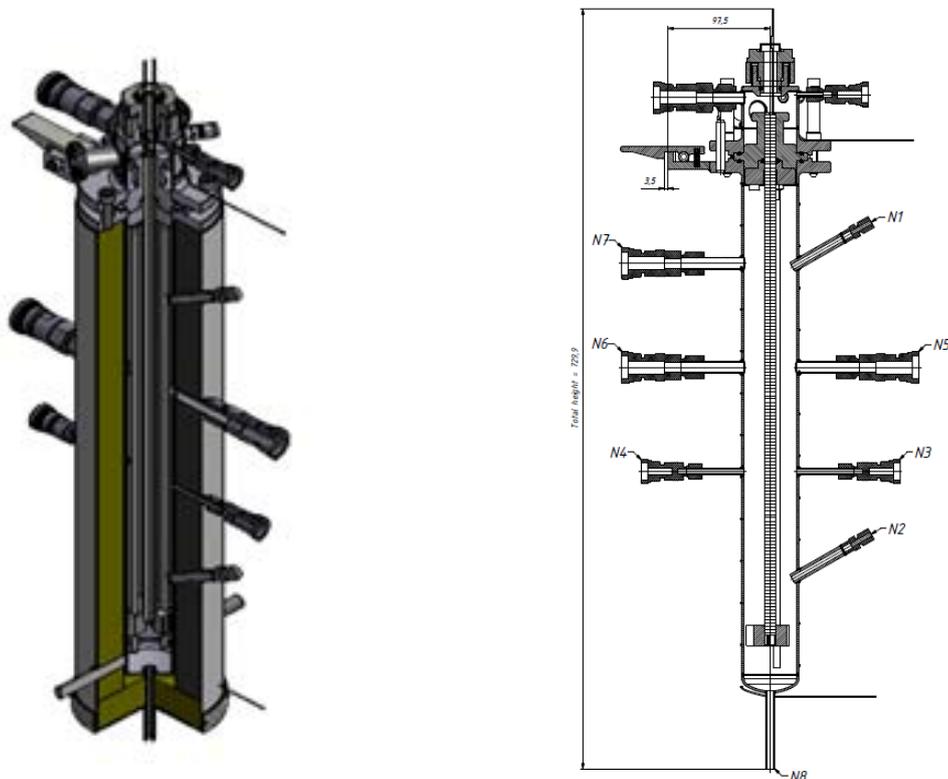


Figure 1. On the left: a 3D cut of the WETFUEL flask. On the right: A cross section of the WETFUEL flask: assembled top and upper reservoir with the inner holder.

A cold trap was installed in the vacuum line to trap water and possible contamination which would come out from the fuel rod during vacuum pumping of the system. However, after the first experiments with spent fuel it became clear that the cold trap was not necessary and it was bypassed for the following experiments. Several thermocouples were used in this setup: one to monitor the temperature inside of the hot cell, another was used in the cold trap, two were used to monitor the lower reservoir and one for the upper reservoir. The thermocouple in the hot cell was set to switch off all heating automatically in case the temperature exceeded 50 °C to protect the plastic covers of the telemanipulators. Similarly, the temperature in the

reservoirs was monitored. Operational temperature of the reservoirs was set at 150 °C but when, due to malfunction, the temperature reaches 200 °C also all heating will be switched off automatically to protect the installation. Two heating cables, type SEI 15/200, from THERMOCOAX were used to heat the reservoirs; one for the lower and one for the upper reservoir. Both reservoirs were insulated by an insulation cord. An extra temperature shield was added after functionality tests to make sure that the plastic cover of the telemanipulators would not come into contact with the hot surface of the top reservoir.

It was impossible to find a gas independent and radiation hardened pressure gauges that could measure both overpressure (up to 3 bar) and vacuum with a good accuracy. A compromise was made using two types of pressure gauges: one for the low and one for the high pressure range. To monitor the the low pressure range (range: $8 \cdot 10^{-4}$ till $1 \cdot 10^3$ mbar), TPR017 Pirani vacuum gauges from Pfeiffer Vacuum were used, as they have shown good radiation resistance in past experiments. The disadvantage of this type of vacuum gauge is that it is not gas independent but requires calibration for each gas. Several PXM pressure transducers from OMEGA were used, the PXM219, PXM359 and PXM459, for monitoring the pressure in the high pressure range. (0 to max 7 bar depending on the PXM). These transducers have the disadvantage of being not radiation hardened and one of them needed to be placed inside the hot cell. A few types of PXM were used for different accuracy and also to see if there was a type which had a longer lifetime under radiation conditions.

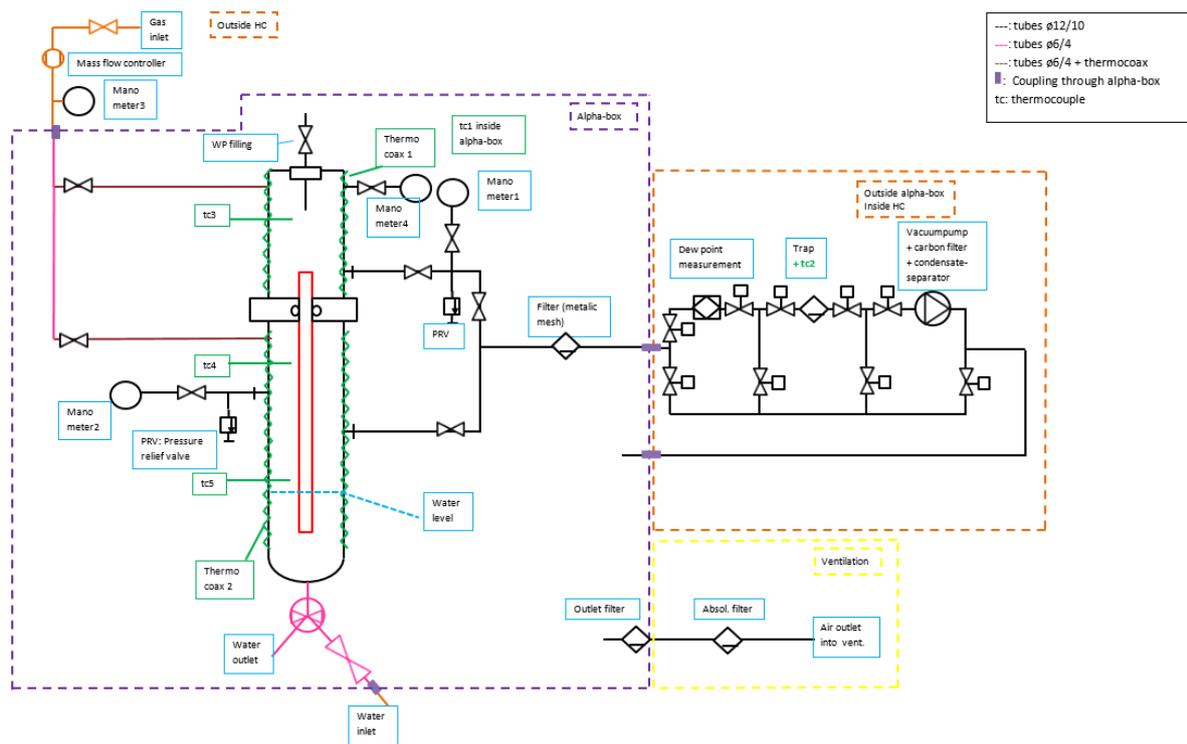


Figure 2. Schematic view of the installation.

The inlets for water and gas were located outside the hot cell. The water reservoir was a 10 L vessel located on the roof of the hot cell. The water which was used in the experiments and in contact with spent fuel became contaminated. For disposal, the contaminated water was evaporated inside the hot cell by use of a normal cooking plate. The gas, either Ar or He was taken from a 10 L bottle. Ar was used for the drying test because it has a higher heat capacity

while He was used in gas flow measurements. The size for the water and gas reservoirs were chosen to ensure that no run-out was possible during experiment but in the case of a valve malfunction the hot cell ventilation would be capable of handling the excess gas amounts. The equipment was tested in cold conditions for several months and no abnormalities were found in operation.

4. Equipment adaptations and lessons learned

The poor radiation resistance of some components and changes introduced to the test protocols required adaptations for the equipment. The first series of tests were performed on a single fuel segment for an extended period of time. This eventually led to vacuum leaks due to degradation of the rubber O-ring seals due to irradiation, probably further accelerated by the elevated temperature. Subsequently the axial flow tests were applied on a number of different fuel rod segments and each time when new segment was installed the seals were renewed. This procedure prevented further vacuum problems with O-ring seals.

Initially the system had plastic vacuum lines which lead to small vacuum leaks during prolonged operation. These vacuum leaks were particularly tedious as they could only be detected in the end of each test when an isolation test was performed to check and demonstrate fuel dryness. The plastic lines were replaced after few months of operation by more robust metallic flexible vacuum lines. The metallic vacuum lines prevented any vacuum leaks but on the other hand led to condensation problems in some of the water vapour tests.

The different types of top pressure meters used, the PXM219, PXM359 and PXM459, were severely affected by the strong radiation field of the spent fuel segment. This led to an offset between the measured and the actual pressure. This degradation was monitored in-between tests by a pressure transducer that was placed at the outside of the hot cell. The general purpose pressure transmitter on the top reservoir, a PXM219, range 0 to 4 bar absolute, with silicon diaphragm was first replaced with a transducer, PXM 359. The PXM359 had a range 0-7 bar absolute and the strain strain gages are placed directly on a stainless steel diaphragm. Both PXM's had the same accuracy(0.25 %) The PXM359 was less effected by the radiation but due to the need for a better accuracy the transducer was replaced again by a silicon type transducer knowing that the transducer would need to be replaced on a regular basis. The third type of transducer that was used was a PXM459 with an accuracy of 0.08% and a range 0 to 2 bar absolute. A typical interval for changing the pressure transducer was around 2 months.

A minor but important adaptation was performed for the top reservoir to allow for an accurate water injection. For this purpose a valve system was fabricated and placed in the inlet of the conductivity meter. Hence, the conductivity measurement capability was lost but it was anyway determined fairly useless as it was known that the top reservoir contained water. With the new valve system, a controlled amount of water (up to 20 mL) could be introduced to the top reservoir using a syringe. With the heating capability of the setup this water served as the source for water vapour.

5. Performance of the equipment

The first approach was to directly measure the gas flow through the rod using a flow meter, which worked fine for mock-up fuel rods but surprisingly failed for the real fuel. Because no measurable flow could be established between the top and bottom, the approach for determining hydraulic properties for the spent fuel segment relied on recording pressure increase and decrease rates in an isolated volume – a method commonly used in leak testing.

Two separate hydraulic measurements were developed, *Figure 3*, to study axial gas flow in the fuel column:

- Test #1: Top and bottom reservoirs were first equally filled with argon to 1.2 bar. The top was then isolated and the bottom pumped to vacuum. Gas leak rate **from** the isolated top volume was directly measured.
- Test #2: Top reservoir was first pumped to vacuum and the bottom reservoir was filled with argon to 3.3 bar. The top was then isolated and gas leak rate **to** the isolated top volume was directly measured.

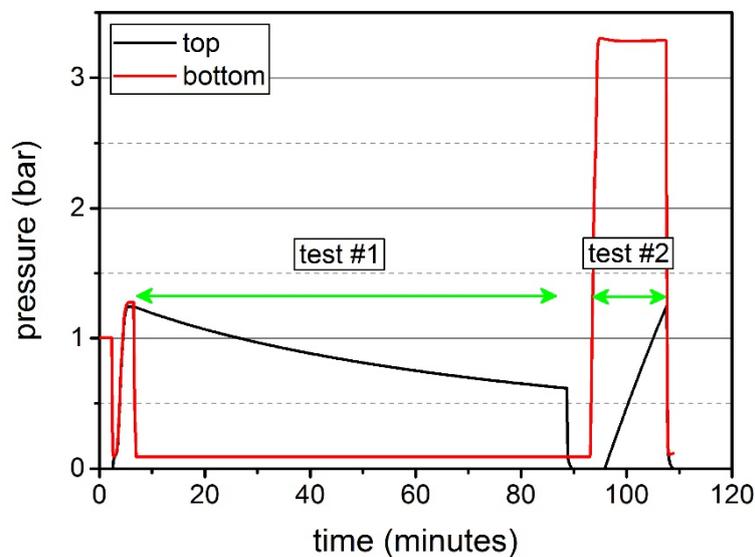


Figure 3. Measurement of axial gas flow using either pressure decrease (#1) or pressure increase (#2) method.

| Test protocol | Leak rate (mbar×L/s) | Leak radius (μm) |
|---------------|----------------------|------------------|
| # 1 | 0.13 ± 0.01 | 88 ± 2 |
| # 2 | 1.19 ± 0.07 | 89 ± 2 |

Table 1: Leak rates for test protocols #1 and #2. The average values are reported with standard deviation from 19 repeated measurement.

To demonstrate the performance of the axial gas flow measurements, leak rates determined from pressure decrease tests (test protocol #1) and pressure increase tests (test protocol #2), which are summarized in *Table 1*. These tests were performed during three months of continuous testing of a single spent fuel segment and demonstrate that the measurement setup and also the spent fuel remained unchanged. The magnitudes of the leak rates for both tests indicate that the gas flow through the spent fuel column was laminar for both protocols. Gas flow path radius was calculated based on the measured leak rate by applying the formulation for frictional-viscous flow according to Eq. (1) and (2) [2]:

$$\dot{n} = \frac{P_1 \times V}{R \times T} = \frac{\pi \times r^4 \times (P_2^2 - P_1^2)}{R \times T \times 16 \times \eta \times L}, \quad (1)$$

$$r = \sqrt[4]{\frac{P_1 \times V \times 16 \times L \times \eta}{\pi \times (P_2^2 - P_1^2)}}, \quad (2)$$

where V is the top volume, L is the segment length, η is viscosity of Ar, and P1 and P2 are top and bottom pressures, respectively. Both protocols yield the same flow path radius as expected. It is noted, however, that the approach likely is an oversimplification for the flow path which in reality consists of axially and radially varying concentration of connecting pores and cracks, and the fuel-cladding gap.

6. Conclusions

A laboratory-scale hot cell installation was successfully developed and installed for investigating the drying principles and axial gas flow in spent nuclear fuel column. Hot cell operation under high radiation field and elevated temperatures has its limitations and compromises were required for various components. Most notably, degradation of O-rings, plastic vacuum lines, and pressure transducers was observed in this work. For O-rings and pressure transducers, replacement was the only viable option while plastic vacuum lines could be changed to more robust metallic vacuum lines. Once the performance was demonstrated on the permeability of the fuel rod segment, the instrument could be taken into service for tests on drying kinetics of leaking spent fuel segments.

7. References

- [1] "Management of Damaged Spent Nuclear Fuel No. NF-T-3.6," IAEA Nuclear Energy Series, Vienna, 2009
- [2] K. Jousten, Handbook of Vacuum Technology, Wiley-VCH Verlag GmbH & Co., Weinheim, Germany, 2016.