

# EXPERIMENTAL SETUP FOR FUEL FRAGMENTATION STUDIES

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## ABSTRACT

The fuel fragmentation phenomenon was identified in the Halden and then the NRC-sponsored test program at Studsvik Nuclear AB. Although the issue was identified years ago and could have regulatory implications a significant gap remain with respect to understanding the fragmentation process, key factors that influence fragmentation and the fragmentation burn-up threshold itself. In order to evaluate fuel fragmentation found in previous LOCA tests (Loss Of Coolant Accident), fuel sections from fuel rods of different burn-ups were heated in air to 1000°C.

To simulate the reduced radial constraint due to ballooning in LOCA-tests, axial cuts (slits) through the cladding were introduced in some samples. Fuel fragmentation results from the heating test agrees well with those from LOCA tests. Revealed by the results from the heating tests is a burn up fragmentation threshold, i.e. above a certain burn up the amount of fuel fragmentation is substantially increased. The focus for this presentation is on the experimental setup, i.e. the sample preparation, in-cell tube furnace and test monitoring are described as well as schematic results.

## 1. Introduction

Severe fuel fragmentation of high burn-up fuel rods have been observed in the Halden test reactor loss-of-coolant-accident (LOCA) integral test since 2007. The issue became a serious matter for the industry after severe fuel fragmentation, at lower burn-up, was also observed in the Nuclear Regulatory Commission (NRC) sponsored out-of-core integral test at Studsvik Nuclear AB early 2011.

A careful review of all the test results indicates fuel fragmentation is primarily driven by burn-up but the threshold may also be dependent on the operational history of the fuel rod. To evaluate the fuel fragmentation phenomenon in an efficient manner, a cost-efficient testing technique; heating of a small fuel test sample with an axial slit in the cladding in air, was developed and evaluated by EPRI [1] and [2].

In order to use the pellet heating technique to investigate the fuel fragmentation phenomenon it must be validated/benchmarked against an accepted testing technique. High burn-up fuel, above the fragmentation threshold, was tested in an air atmosphere and showed fragmentation behaviour similar to the NRC-sponsored integral tests, using material from the same parent rod.

In the air atmosphere tests there is a potential that U<sub>3</sub>O<sub>8</sub> formation could destabilize the fuel and cause fuel fragmentation. Hence a test sample was heated to target temperature in inert gas atmosphere. The test in inert gas showed good agreement with the test in air. To further validate the technique, pellet heating test was also conducted with fuel below the fragmentation threshold and the result is also in agreement with integral tests using materials from the same parent fuel rod. After successful validation of the technique, tests were

conducted to evaluate potential pre-transient power history effect and fuel fragmentation temperature threshold.

## 2. Furnace setup

Fuel heating tests are performed in a radiant tube furnace installed in a hot cell. The furnace has three individually controlled heating zones. Each heating zone is 80 mm long and the total heated zone is 240 mm in length. A 500 mm long quartz tube with a diameter of 30 mm is normally used for the heating tests. Fuel samples are tested either under ambient air atmosphere or in a controlled inert gas atmosphere, typically up to a temperature around  $1000\pm 5$  °C. The sample temperature is either directly recorded by a thermocouple attached on the sample or controlled indirectly based on a calibration procedure, relating the sample temperature to a thermocouple fixed on the quartz tube in the centre of the furnace. Fast heating rates, typically in the order of 10 °C/s, can be obtained by preheating the furnace to the target temperature, before inserting the sample. Figure 1 shows the furnace set-up for tests in ambient air, installed inside a hot cell. These tests are normally documented by means of a video camera with a microphone (visible on the left side of Figure 1). For tests with inert gas, connector pieces are attached to the ends of the quartz tube, see bottom picture of figure 1. A typical temperature – time curve is shown in Figure 2.

The furnace temperature is measured using a N-type thermocouple located at the axial middle of the furnace tube. The heating test is conducted by inserting a room temperature sample into the pre-heated furnace and extracting it once the target temperature is reached.

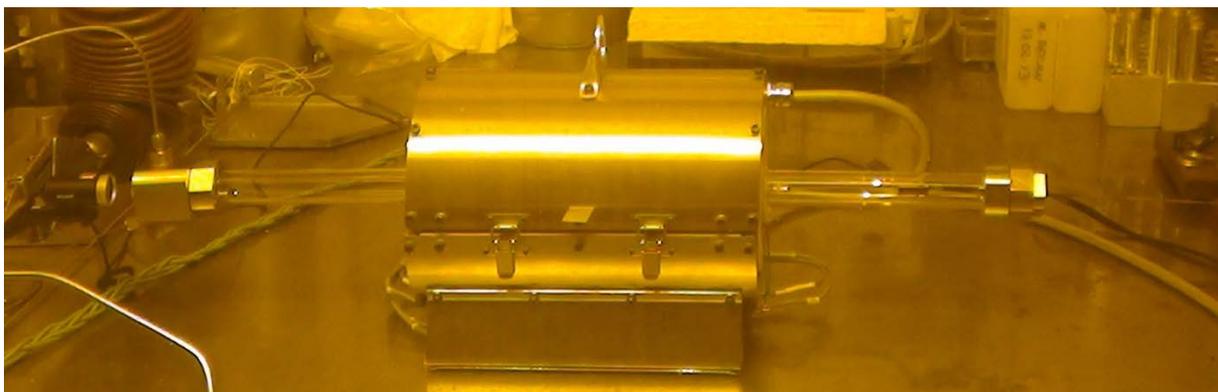
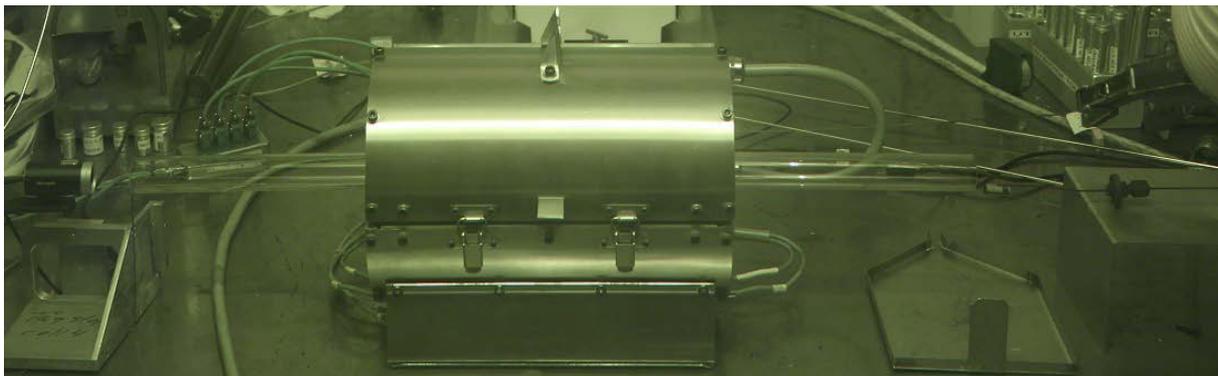


Figure 1  
Furnace used for fuel heating tests installed in hot cell. Air atmosphere setup (top) and inert gas setup (bottom). The camera is visible to the left of the quartz tube.

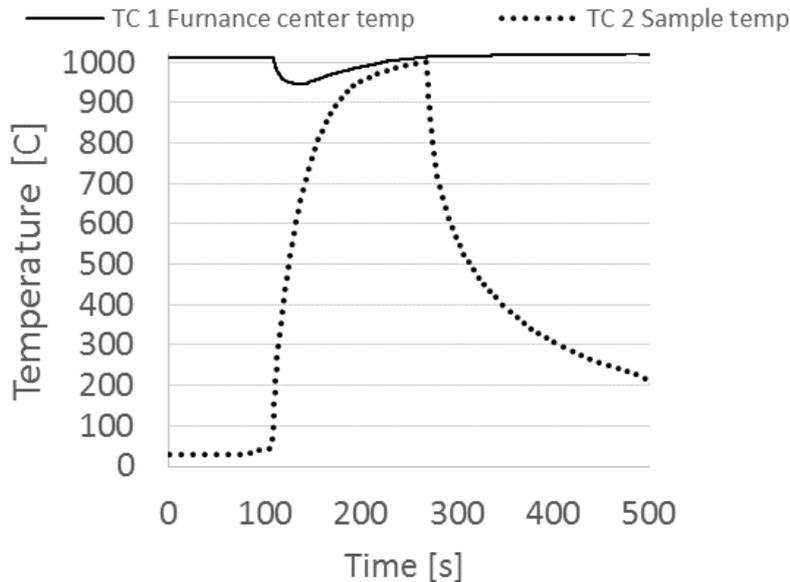


Figure 2

Plot of furnace (solid line) and sample temperature (dotted line) versus time, recorded in a typical fuel heating test.

After extraction from the furnace and cool-down, each sample is taken through the following post-test procedure: The sample post-test condition is documented by photographs taken with the webcam. The clamp with the thermocouple is carefully removed and the sample is weighed on a precision balance. Any fuel fragments fallen out due to the handling are collected, photographed and weighed. The furnace tube is carefully emptied of any fuel fragments and powder. The collected fuel material from the tube is photographed and weighed. Finally visual inspection and dimensional measurements are performed. The post-test length, width of the slit and the diameter of each sample are measured.

Typical data from a temperature test are:

- Temperature versus time recorded by the thermocouple fixed on the sample and by the thermocouple in the centre of the furnace.
- Weight change and fuel loss of the sample
- Fuel fragment distribution in size and weight by sieving and weighing.
- Video recording including sound track.

### 3. Sample preparation

A typical heating test sample is two pellets long. Gamma scan data is used to guide cutting of test samples from the father rod in order to obtain one complete pellet in the centre of each test sample. In order to simulate the reduced radial constrains of the balloon in the LOCA-tests an axial slit through the cladding is made with a 1.0 mm thick cutting disc, see figure 3. Care is taken to ensure the cutting depth into the fuel pellet is no deeper than 0.5 mm. After cutting the samples are weighed on a precision balance with an accuracy of 0.1 mg. The samples are also visually inspected and the length, width of the slit and the diameter of each sample are measured.

For a typical heating test a thermocouple is directly attached to the cladding of the test sample using an Inconel X-750 clamp. This enables accurate sample temperature measurements and insertion/extraction of the test sample from the furnace. The sample is centred in the furnace tube by the use of a pair of steel spacers mounted 10 cm and 35 cm from the sample centre. The setup is illustrated in Figure 4.

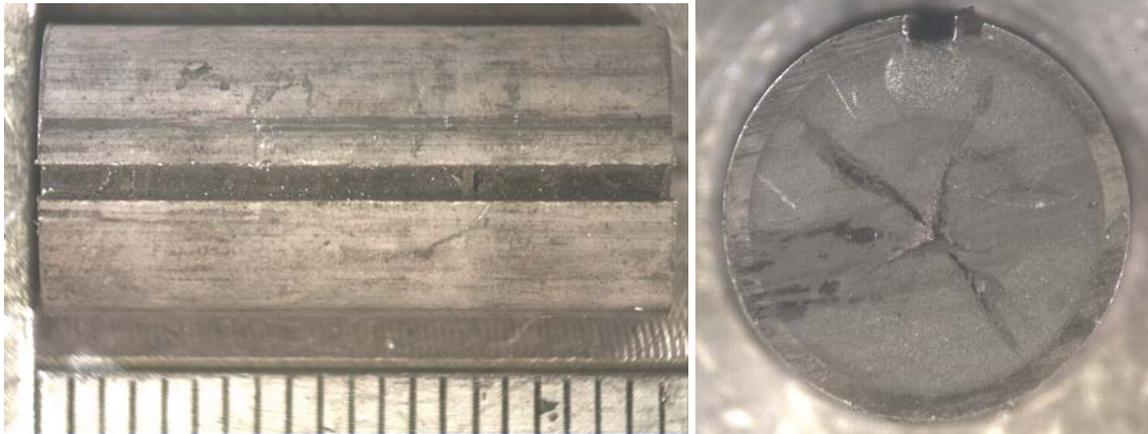


Figure 3

A typical sample is two pellets long containing a complete pellet in the centre. An axial slit is cut through the cladding to simulate the ballooning of an LOCA-test.



Figure 4

An Inconel X750 clamp attaches the thermocouple to the sample. Two stainless steel spacers centres the sample inside the quartz tube of the furnace

#### 4. Results

Sample and furnace temperatures were acquired during the heating tests. Each test was also recorded on video with sound using a webcam placed inside the hot cell. The start of video recording and temperature data acquisition was performed manually on different computer systems, but an effort was made to start both simultaneously. Thus, the temperature data and any features observed on video can be correlated within a few seconds. The camera was placed to the left in Figure 8. It looks directly into the furnace tube during the full test sequence. The video and sound recordings provide a very good documentation of the sample behaviour in the heating test. For example, the videos show sparks, smoke emissions and ejection of fuel fragments from each sample. The sound recording alone provides a possibility to analyse peaks of sound intensity which could be associated with the bursting of gas bubbles in the fuel.

Figure 5 show some typical photos from a heat tested sample with a burnup clearly above the fragmentation threshold.

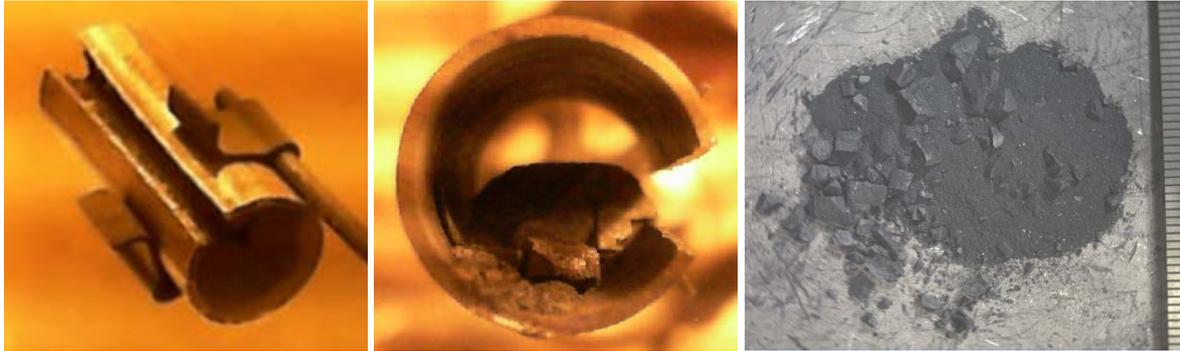


Figure 5

A fragmented sample after test showing the thermocouple clamped to the sample (left), complete fuel loss (centre) and collected fuel fragments (right, the scale to the right are in millimetres).

## 5. Acknowledgments

The institutions and programmes are acknowledged for the contributions to this paper: SCIP III open program proposal, OECD/NEA, EPRI.

## 6. References

[1] Snis, N., Heating test of high burnup fuel – Influence of irradiation history on fuel fragmentation, Studsvik Nuclear AB, report, Studsvik Report N-13/221.

[2] Yueh K., Snis, N., Mitchell, D. and Munoz-Reja, C., Fuel Fragmentation Data Review and Separate Effects Testing, Paper No. 100117, Proceedings of WRFPM 2014, Sendai, Japan, September, 14-17, 2014.