IN-PILE MEASUREMENTS OF FUEL ROD DIMENSIONAL CHANGES UTILIZING THE TEST REACTOR LOOP PRESSURE FOR MOTION

Richard S. Skifton and Kurt L. Davis
Idaho National Laboratory
PO Box 1625, Mail Stop 3531, Idaho Falls, ID 83415, USA,
Richard.Skifton@inl.gov; Kurt.Davis@inl.gov

John C. Crepeau
University of Idaho, Department of Mechanical Engineering
875 Perimeter Drive, MS 0902, Moscow, ID, 83844-0902, USA
crepeau@uidaho.edu

Steinar Solstad
Institute for Energy Technology
Os Allé 5 N-1777 Halden, Norway
steinar.solstad@ife.no

ABSTRACT

Different types of materials are being considered for fuel, cladding, and structures in existing and advanced nuclear reactors. These materials can undergo significant dimensional changes during irradiation. Currently in the US, such changes are measured with the 'cook and look' method (i.e. repeatedly irradiating a specimen for a specified period of time, and then removing it from the reactor for evaluation) – which leads to costly and time consuming experiments. In addition, such techniques provide limited data, and handling may disturb the phenomena of interest. Therefore, in-pile detection of geometric changes is needed to understand real-time behavior during irradiation testing of fuels and materials in high flux US Material and Test Reactors (MTRs). The developmental results of an advanced Linear Variable Differential Transformer (LVDT)-based test rig capable of detecting real-time changes in diameter or length of fuel rods or other material samples during irradiation in US MTRs are presented. The LVDT is being developed at the Idaho National Laboratory (INL), and will provide experimenters with the capability to measure dimensional changes associated with fuel and clad swelling, pellet-clad interaction, and crud buildup.

The LVDT design utilizes the MTR's loop pressure to drive the test specimen at a constant rate. This leads to a simplified construction which only requires three pressure boundary penetrations. Further, the LVDT pressure boundary is a leak tight hydraulic ram capable of actuating under low differential pressure (e.g. 1 psid), and is able to survive the high irradiation tests at Pressurized Water Reactor (PWR) conditions.

Key Words: In-Pile Deformation and Measurement Instrumentation

1 INTRODUCTION

Evaluating real-time changes in fuel and cladding diameters during irradiation testing can be used to characterize phenomena such as the buildup of "crud" that can adversely affect heat transfer, pressurization from fission gas release, and pellet-clad mechanical interactions. It goes without saying that such diameter measurements could be critical in advancing the knowledge base related to irradiation effects on fuels and cladding.

Three international laboratories are developing test rigs [1], [2] capable of measuring cladding diameters during irradiation testing in materials test reactors (MTRs). The first is the Institute for Energy Technology/Halden Reactor Project (IFE), the second is Commissariat à l'Énergy Atomique (CEA), and third is the Idaho National Laboratory (INL). The IFE and CEA test rigs are described below to provide background information; section 2 will discuss in detail the INL test rig.

1.1 IFE Diameter Gauge Test Rig

The IFE diameter gauge [3], [4] enables real-time in-pile measurements of cladding diameters for assessing cladding creep, pellet-clad mechanical interaction, fuel creep/relaxation, and the buildup of fuel rod crud deposits. A representative IFE standardized test rig is shown in Figure 1(a). IFE relies on linear variable differential transformer (LVDT)-based technology in their diameter gauge. The diameter gauge itself is shown in Figure 1(b) with two primary coils and two secondary coils wound on a ferritic bobbin. A change in distance between each of the secondary coil loops and the armature alters the balance between the signals generated in the two secondary loops, leading to a change in the output signal (difference of the two secondary coil signals). The output signal is then correlated to changes in the fuel rod diameter.

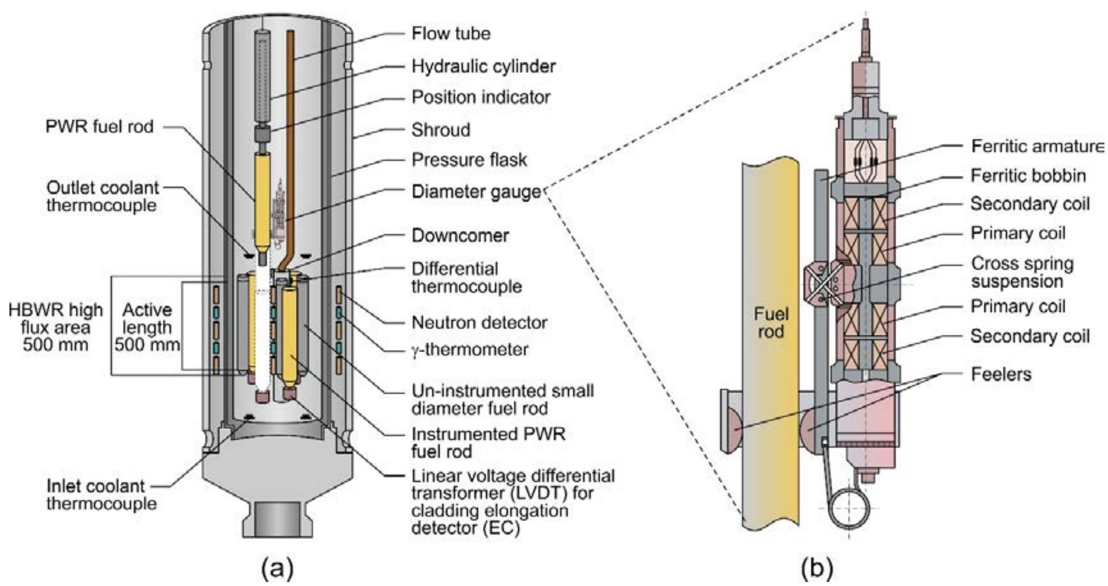

Figure 1. IFE fuel pellet cladding mechanical interaction/crud deposition test rig (a) with diameter gauge (b) [3, 4].

In some test rigs, the diameter gauge travels along the fuel rod using an in-core hydraulic drive and positioning system, while in other test rigs (as is the case here); the fuel rod is moved by the hydraulic drive. The accuracy of the diameter gauge is ± 2 μm, and a calibration is performed in conjunction with each diameter trace by having calibration steps on both ends of the fuel rod. The IFE diameter gauge has standard operating pressure and temperature of 165 bar and 350 °C, respectively. However, modifications to IFE LVDTs, as discussed in references [5] through [8], should allow its operation at much higher temperatures (i.e. 700°C).

1.2 CEA Diameter Gauge Test Rig

Recently, CEA, IFE, and the Technical Research Center of Finland collaborated on the Mechanical Loading Device for Irradiation Experiments (MELODIE) test rig [9]. Specific LVDT and DG components – designed and produced by IFE – related to elongation and diameter measurements have been irradiation tested in the OSIRIS reactor. Ultimately, this test rig will be deployed in the new Jules Horowitz Reactor.

The MELODIE test is designed to provide real-time biaxial elongation and diameter change data. The test rig will be used to collect data in-core from a pre-oxidized pressurized water reactor (PWR) fuel cladding tube (90 mm in length) at 350 °C, irradiated at peak fast neutron fluxes as high as 4.5×10^{14} n/cm^2-s (E >0.1 MeV), with nuclear heating up to 9.5 W/g. The MELODIE test rig – with a length of 1.60 m and a diameter of 23.50 mm – was designed to be deployed in a sodium-potassium filled double-walled container often used as a standardized test rig in the OSIRIS reactor. Stress and biaxial strain are applied in the MELODIE test rig using three independent high pressure helium circuits.

2 INL DIAMETER GAUGE TEST RIG

INL researchers have recently initiated evaluation of an IFE diameter gauge to identify enhancements required for deployment in the Advanced Test Reactor (ATR). This section summarizes the status of these efforts to develop an appropriate diameter gauge and associated testing equipment (e.g., electronics, test rig, etc.). The INL Diameter Gauge Test Rig consists of two main sections: the LVDT sensor, and the Hydraulic Piston. The sensor utilizes the IFE diameter gauge discussed previously, and the piston is a new concept design for a one-dimensional, translating, hermetic seal.

2.1 Diameter Gauge Design and Build – LVDT

The conceptual design of the diameter gauge test rig can be seen in Figure 2. The test rig employs the IFE diameter gauge similar to that of the IFE as shown in Figure 1(b). This particular gauge is capable of measuring a diameter of about 10 mm with a reported accuracy of about ± 2 μm, but, in theory, any rod diameter is possible with a typical measurement range of ±0.5 mm. Design parameters include a maximum temperature of 325 °C with an allowable working pressure of 165 bar. Unlike the IFE and CEA test rigs – which both use an LVDT-type device to track axial displacement of the diameter gauge – this test rig relies solely on a constant velocity hydraulic ram and a characteristic calibration zone to record displacement. The constant velocity – starting off from the calibration zone – can be integrated with time to give axial location along the specimen.

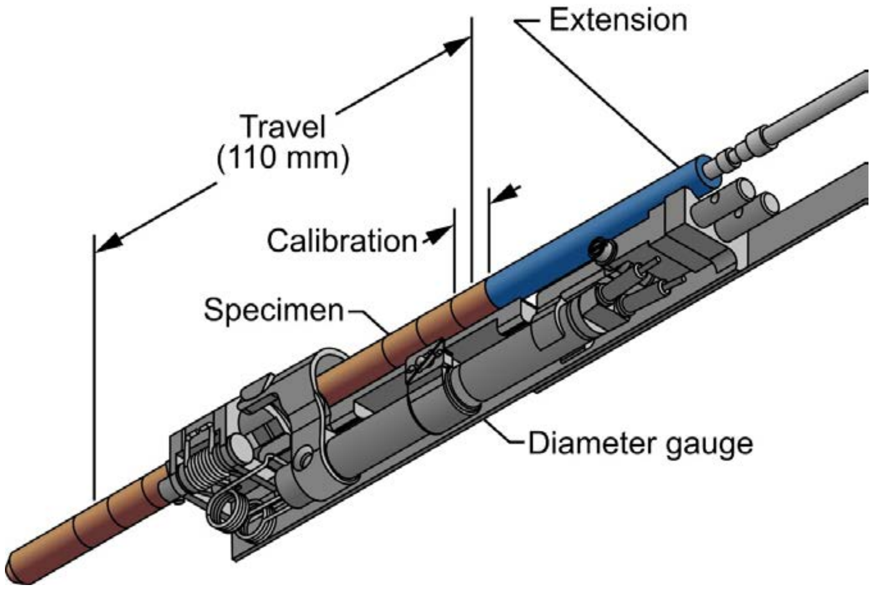

Figure 2. Conceptual design of INL-designed diameter gauge test rig proposed for ATR.

2.2 Diameter Gauge Design and Build – Piston

In order to use the ATR loop pressure to drive the system, a one-dimensional, translating, hermetic seal is needed with robust material to withstand the high temperature and neutron flux during the in-pile testing. A metal on metal seal was designed in the form and shape of a piston and cylinder. The piston rings used to keep the seal can be seen in the detail of Figure 3, where two rings – when rotated 180° from each other – have the ability to respectively seat inside the other. This allows for the inherent gap necessary in piston ring design to be sealed, in turn, by the other. The entire assembly can then be translated in the axial direction, at very low differential pressure (e.g. 1 psid), and maintain the seal throughout the process. In the current design, a redundancy of two piston ring assemblies in series was utilized to increase the reliability of the seal.

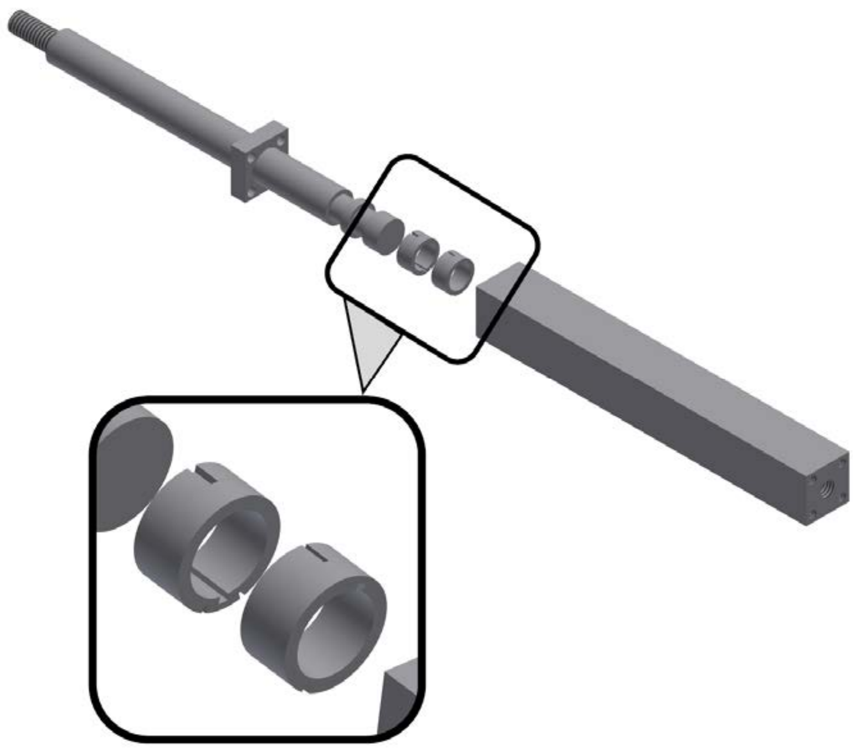

Figure 3. Piston cylinder assembly with zoomed view of piston ring interaction.

2.3 Benchtop Test Results of the INL Diameter Gauge

To evaluate the current design, a calibrated test specimen was developed as seen in Figure 4 with metrology information. Measurements of the diameter of the rod were recorded as a function of time as the test specimen was pulled through the diameter gauge at the constant velocity – typically between 1.25 mm/sec and 2.22 mm/sec. Temperature of the specimen and any foreign contaminants were closely controlled throughout the experiment. Further, when the diameter gauge travels across the various calibration zones machined into the specimen, characteristic peaks were recorded by the diameter gauge. The distance between these characteristic peaks is a known value, so axial displacement was evaluated by interpolating between them (i.e., superimposing the displacement scale over the time scale). Figure 5 shows experimental data, superimposed over simulated data, for a corresponding travel time of 50 seconds (i.e. constant velocity of 2.22 mm/sec over the length of the specimen).

On the benchtop scale, the standard error of the measured results to expected (calibrated) values was calculated using

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-1}} \quad (1)$$

with y being the measured results, ŷ is the expected (calibrated) values, i is the sample index, and n is the number of samples. Upon calculating equation 1 on the experimental results, it was found that the standard error was approximately 2.5 µm; which is an approximate relative error of 0.03% of the rod diameter. Further, for the measurements of axial locations along the rod, the standard error between measured and calculated (using the average velocity over the entire travel period) locations was 62.7 µm; which equates to an approximate relative error of 0.6%. These values were similar over repeated tests. This shows that the constant velocity based LVDT has potential in giving precise and accurate readings of both clad swelling, and any axial elongation that may occur.

2.4 Possible Error Sources to the Diameter Gauge Test Results

Hydraulic ram data suggest that the variation in velocity could result in a displacement error of ± 20 µm over the 110 mm of travel. Another source of displacement error could be attributed to the diameter gauge pad contact point with respect to the test specimen. Figure 6 is a radiograph of the diameter gauge with the test specimen inserted. Measurements taken on the radiograph indicate that the error caused by the contact/alignment of the pad with the specimen is greater than the velocity error. Pad wear will also result in measurement error. In that vein, computed tomography (CT) provides a higher degree of accuracy than radiography. CT scans are planned to evaluate pad alignment, contact and wear.

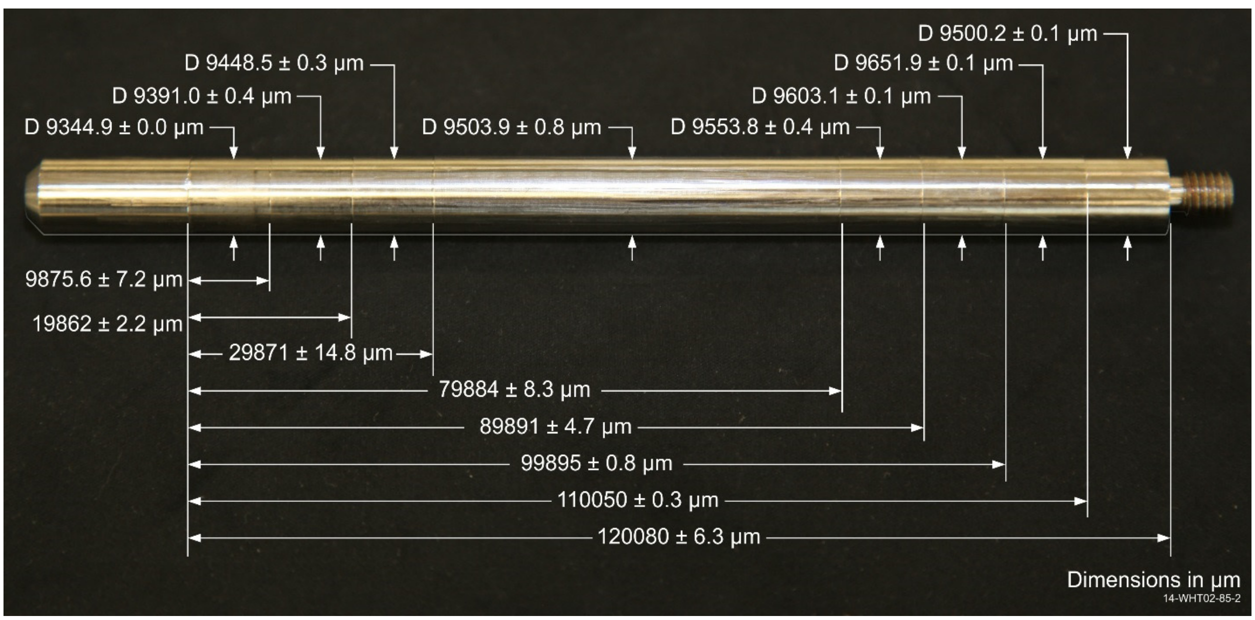

Figure 4. Test specimen with specific dimensional zones. Metrology information is shown with the measured variances.

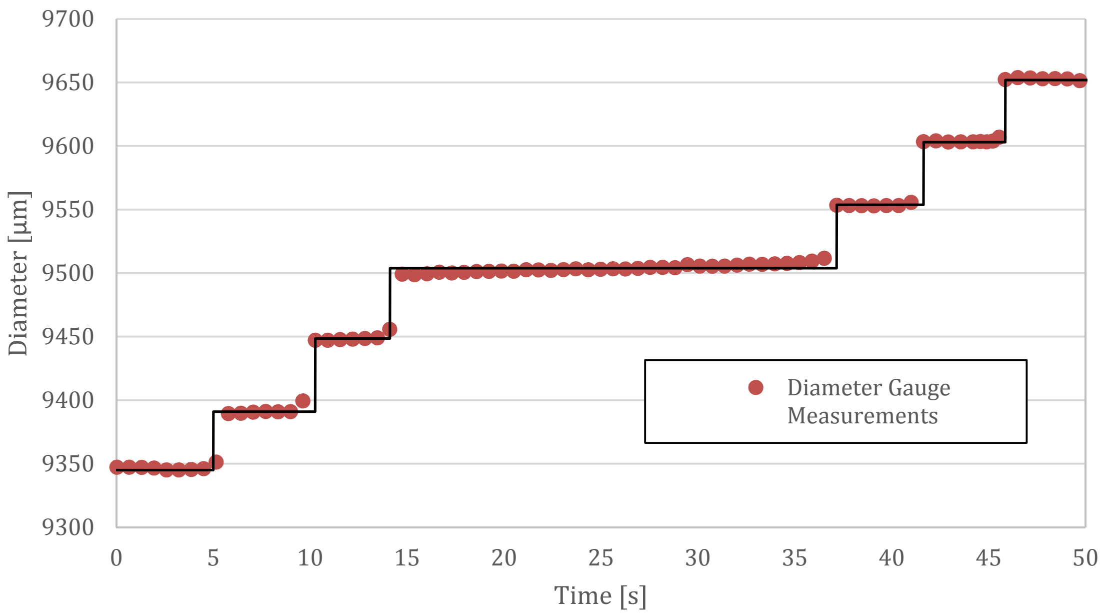

Figure 5. Results from the Diameter Gauge apparatus on the benchtop scale at a constant rate of 2.2 mm/sec.

2.5 Further Tests of the INL Diameter Gauge

As mentioned previously, bench top evaluations have been utilized to characterize the performance of the diameter gauge to determine diameter measurement precision and accuracy, axial measurement accuracy, and scan speed variation. The next step would be to try the apparatus in an autoclave environment. The first test would be at room temperature, but at the maximum allowable working pressure for the diameter gauge (165 bar) to shake down any pressure differential problems while driving the piston assembly. The second test would be conducted at typical PWR conditions (315°C and 155 bar). The final test would be to rerun through benchtop testing at the conclusion of the autoclave testing to verify that diameter gauge performance was unaffected by temperature and pressure testing.

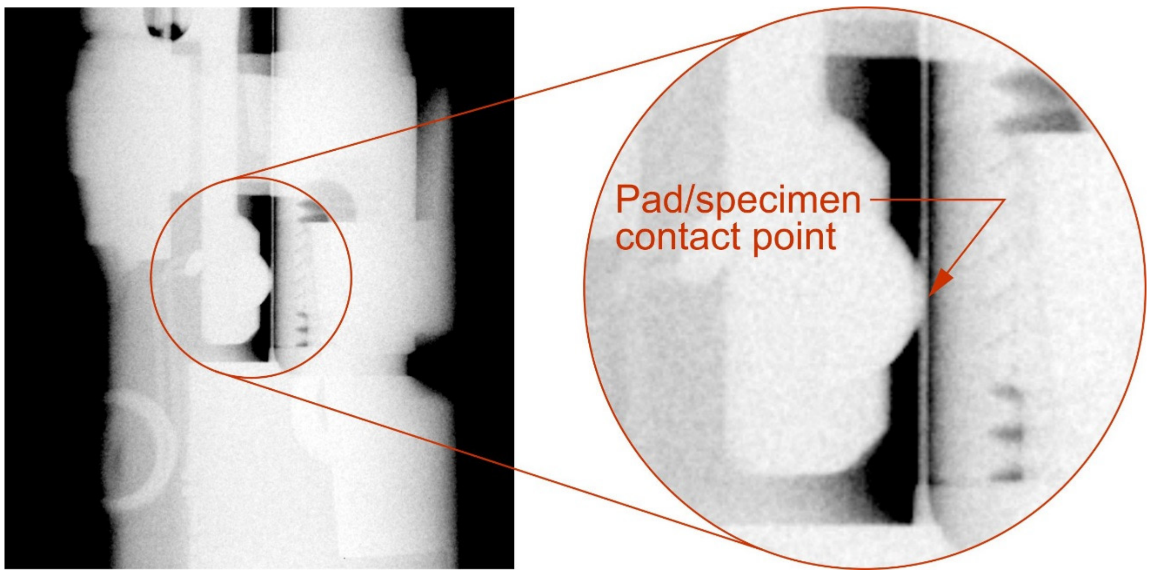

Figure 6. Radiograph of specimen inserted into diameter gauge.

3 CONCLUSIONS

The design, build and testing of a new irradiation test rig, capable of measuring real-time changes in specimen diameter, has been completed. The main design component being constant velocity of a specimen through the sensor – driven by the MTR loop pressure. A unique piston design was utilized to perform at high temperatures and pressures and with relatively low activation to neutron flux; all while maintaining a hermetic seal. The sensor has shown to be precise and accurate within 0.03% of a 10 mm diameter simulated fuel rod.

4 ACKNOWLEDGMENTS

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References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government, any agency thereof, or any company affiliated with the INL.

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