NONDESTRUCTIVE PRESSURE MEASUREMENT TECHNIQUE FOR IRRADIATED NUCLEAR FUEL RODS

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ABSTRACT

Commercial nuclear fuel rods are pre-pressurized with helium before irradiation. During irradiation, the rod internal pressure (RIP) increases due to cladding dimensional changes and pellet fission gas release. RIP is a limiting parameter for rod operation and is a barrier to achieving higher fuel burnup. Currently, rod puncture is the only method used to measure RIP, which is a destructive method. Because of the challenges and cost associated with handling irradiated fuel, the existing database on RIP is extremely limited. This paper presents progress towards developing a novel acoustic-based nondestructive examination method to accurately measure the internal gas pressure in pressurized containers without the need for puncturing the pressure boundary, with an emphasis on applications to spent nuclear fuel (SNF) rods and radioactive material dry storage canisters.

1. Introduction

Commercial spent nuclear fuel (SNF) rods are pre-pressurized with helium before irradiation. The pre-pressurization magnitude varies with fuel design; a typical 17x17 pressurized water reactor (PWR) fuel rod is pressurized to ~300 psi (2.1 MPa) at manufacture. During irradiation, the rod internal pressure (RIP) increases due to the production of fission gases (xenon, krypton, etc.) and volumetric changes due to swelling and rod cladding irradiation growth. During post-irradiation storage, the RIP continues to increase as decay produces helium gas. Because rod puncture is the only method currently available for measuring RIP and is a "one-time" destructive examination, only SNF rods sent to a hot cell for examination have been measured and empirical RIP and fission gas data are extremely limited. The Electric Power Research Institute (EPRI) summarized the data available worldwide in 2013 [1], and less than 100 data points are available.

RIP is a limiting parameter for rod operation and currently is a barrier to achieving higher fuel burnup. Higher predicted RIP at the onset of postulated reactivity insertion and loss-of-coolant accidents results in lower predicted safety margins. Further, higher RIP and higher burnup SNF rods are known to be susceptible to a phenomenon known as hydride reorientation. Typically, hydrogen taken up by the SNF cladding during reactor operation is precipitated in hydride platelets that are oriented circumferentially in the fuel rod cladding (depending on its texture). If high-RIP, high-burnup SNF cladding is subjected to a high-temperature transient such as that experienced during vacuum drying in preparation for dry storage, the hydrides can reorient radially, potentially reducing the load-carrying capability of the cladding with potentially negative impacts on future transportation and storage of the SNF rods. It is worth noting that the overall fuel cost per reactor is significant at ~$1.5B [2]; therefore, a burnup increase due to accurate RIP measurement should lead to significant fuel cost savings and a more precise knowledge of safety margins.

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A technique to measure the RIP of SNF nondestructively at the reactor site can provide pivotal information for the power industry and for the Department of Energy. Similar techniques are likely useful in other applications, such as sealed dry storage canisters. This paper describes the Tube Acoustic-based Pressure and Stress (TAPS) measurement system being investigated by ORNL and documents the results obtained to date.

2. Approach

A typical light water reactor (LWR) fuel rod includes a void space at the top and/or bottom called the "plenum." The plenum provides expansion volume for fission and decay gases so that the RIP is maintained below the maximum design pressure. The plenum typically includes a compression spring to hold the fuel pellets in place. The proposed nondestructive examination (NDE) technique takes advantage of the rod plenum to measure pressure in the rod by measuring the time of flight of an acoustic pulse through the rod cladding. The unique combination of acoustic probes provided by the TAPS measurement system is expected to achieve a high degree of accuracy without damaging the SNF rod. An acoustic impulse is applied by an ultrasound probe and is received by another probe, as illustrated in Fig. 1.

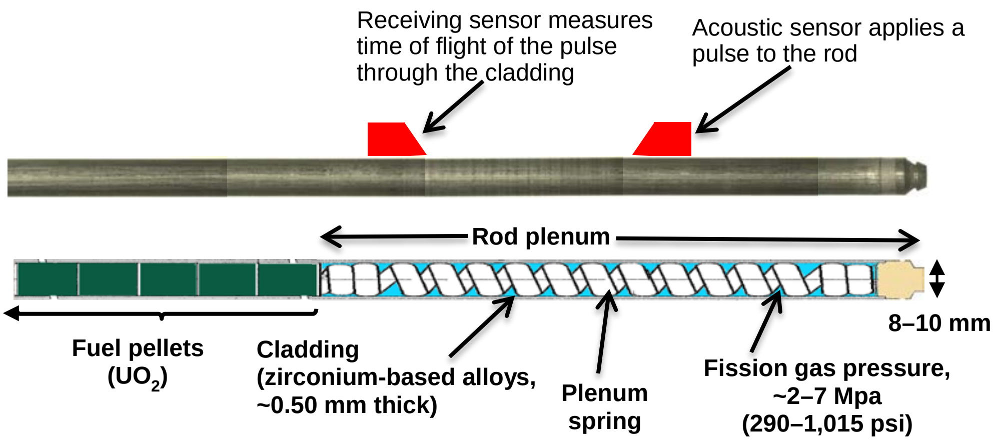

Fig. 1. Typical LWR fuel rod geometry (bottom) and the placement of the TAPS acoustic probes to measure the rod internal pressure by measuring the time of flight of an acoustic impulse through the fuel rod cladding (top).

Past efforts to measure the pressure of SNF rods without puncturing them relied on single sensor measurements and had limited success [3–6]. For example, Rosenkrantz's studies indicated that wave propagation through the rod fill gas showed poor real-time performance, had limited range, and was gas composition dependent, requiring a large number of calibration curves [3,4]. The presence of the plenum spring introduced multiple echoes and strong signal losses which resulted in reduced accuracy (>10%). Thus, in the past, simple acoustic measurements across the rod plenum have not produced accurate RIP measurements.

3. Methodology

The TAPS measurement system introduces an acoustic wave, via one of the probes, that travels through the mediums to the receiving sensors, as shown in Fig. 1. The travel time of the wave is measured, and the internal gas pressure is inferred based on the derived relationships between pressure and time of flight.

For a cross-plenum measurement, the speed of sound through the gas medium is dependent upon the composition of the gas mixture and varies linearly with gas pressure. For an ideal gas, the pressure effect on the speed of sound is very small; however, for higher pressure gas mixtures, the effect can be significant. Because this design does not require cross-rod measurement, this dependence is eliminated.

For the TAPS through-cladding measurement, further illustrated in Fig. 2(b), the propagation of the reflected acoustic shear wave is derived from acoustoelastic [7] and thin shell theory [8]. The RIP produces a stress in the material that influences the ultrasonic wave velocity in the wall. The relationship between pressure and shear wave traveling time is given by

$$\Delta p = \frac{E}{L}\frac{d}{R}\frac{(t_s - t_s^0)}{t_s^0},$$

where *E* is Young's modulus, *L* is a constant related to the second- and third-order elastic constants, *d* is the cladding thickness, *R* is the rod internal radius, t_s^0 is the wave travel time when RIP=0, and $t_s$is the travel time at a non-zero RIP.

Given the standard cladding alloys and rod geometries used, the expected t_s^0 can be tabulated. The shear wave velocity is expected to be on the order of 2,350 m/s for Zircaloy [9,10], for a travel time of ~42.55 µs (10 cm probe distance) and is easily measured with current state of the art. The RIP of the SNF rods to be measured in situ ranges from 1 to 6 MPa, and the rod cladding temperature ranges from 38 to 300°C.

4. Experimental Setup for Proof of Principle

Fig. 2 shows the test setup for proof of principle of the TAPS measurement system. Piezoelectric transducers (PZT) were selected for the initial experiments. Commercially available 10 MHz and 5 MHz angle beam transducers have been used with modified wedges. Several couplants between the wedge and the test rod were investigated for use with the in-air measurements. When the probe was located on the bottom, as shown in Fig. 2(a), the weight of the test rod provided for good contact conditions. When the probes were placed above the test rod, as shown in Fig. 2(c), a weight was placed on each probe to ensure good contact between the test piece and the wedge. Note that the targeted final application is underwater, and therefore water is expected to function as the couplant when the configuration progresses to spent fuel pool applications. A pulser-receiver is used to control the PZT pulse and to capture the signal from the receiving transducer for processing. An oscilloscope is used to monitor the wave amplitude and measure time of flight. Each datapoint is the average of 2,000 time of flight measurements. In addition, the received waveforms are averaged 100 times to reduce noise.

Several surrogate rods were used for this study, including:

- unirradiated pre-pressurized Zircaloy-2 (Zirc-2) and Zircaloy-4 (Zirc-4) short fuel rod cladding segments provided by EPRI having approximately the same volume at four known pressures (0, 30, 100, and 500 psig);
- pre-pressurized rods made of stainless steel tubing at three known pressures (500, 1,000, and 1,500 psig); the rods had the same inner and outer diameters but were fabricated to different lengths (7, 8, 9 and 10 in.) to produce four different volumes;
- a stainless steel variable pressurization rods, as shown in Fig. 3, that was designed and fabricated for this investigation. The variable pressurization rod was also instrumented with three strain gauge rosettes (one at each end and one at the center) to provide a direct measurement of the strain imposed by the rod internal pressure.

The test fixturing allowed for variable sensor spacings. All tests were performed at room temperature, but because the RIP of the very small gas volume included in the test rods can be greatly influence by only a few degrees of temperature change, temperature was also measured. For example, simply holding the test rod in your hand can increase the RIP by more than 25 psig.

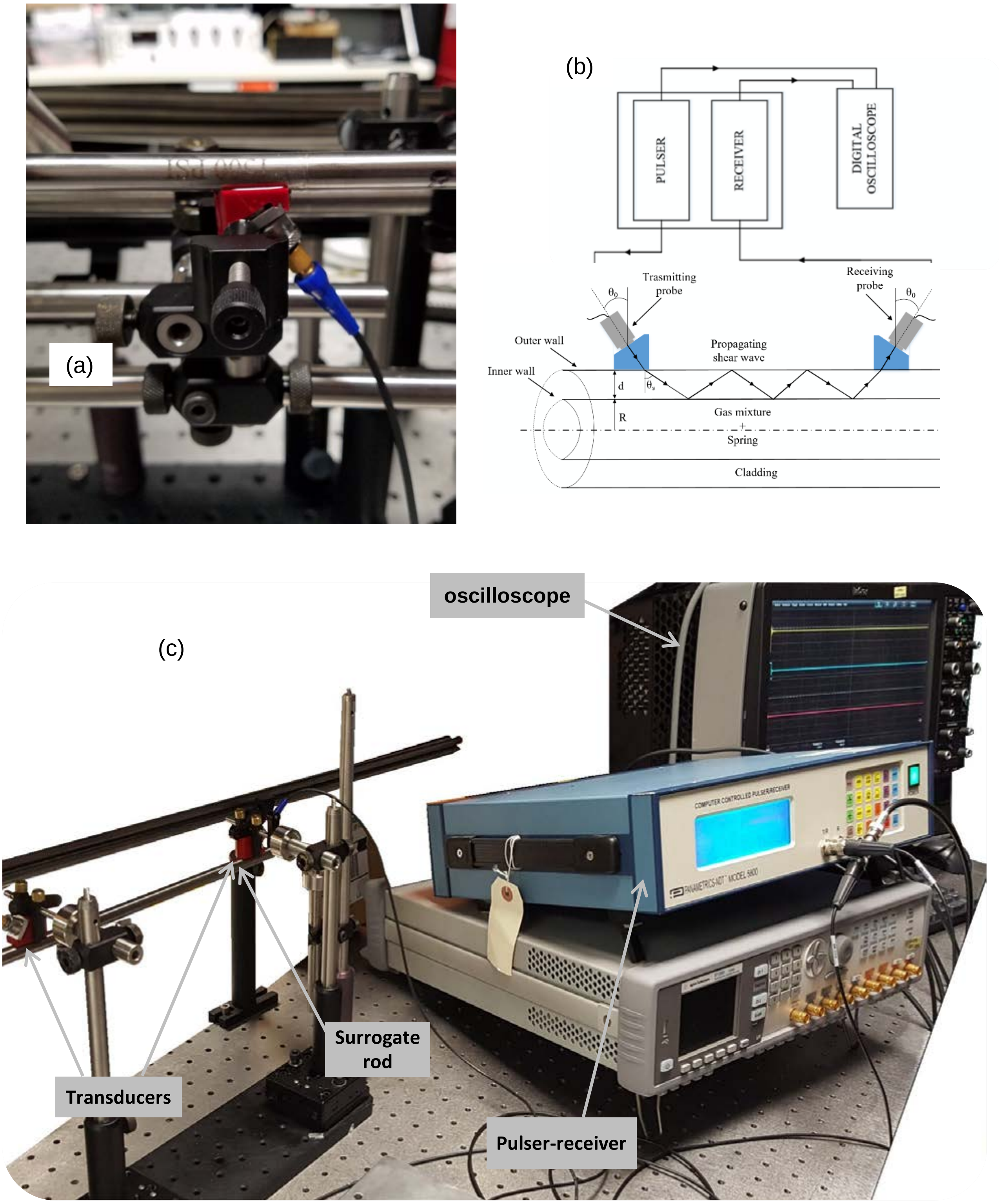

Fig. 2. Experimental setup for unirradiated pressurized fuel rod cladding and stainless steel rod tests: (a) both the sending and receiving transducers are fitted with customized wedges and are clamped in place, (b) a schematic describing the impulse application and sensor functionalities, and (c) the test setup with the oscilloscope, pulser-receiver, and waveform generator.

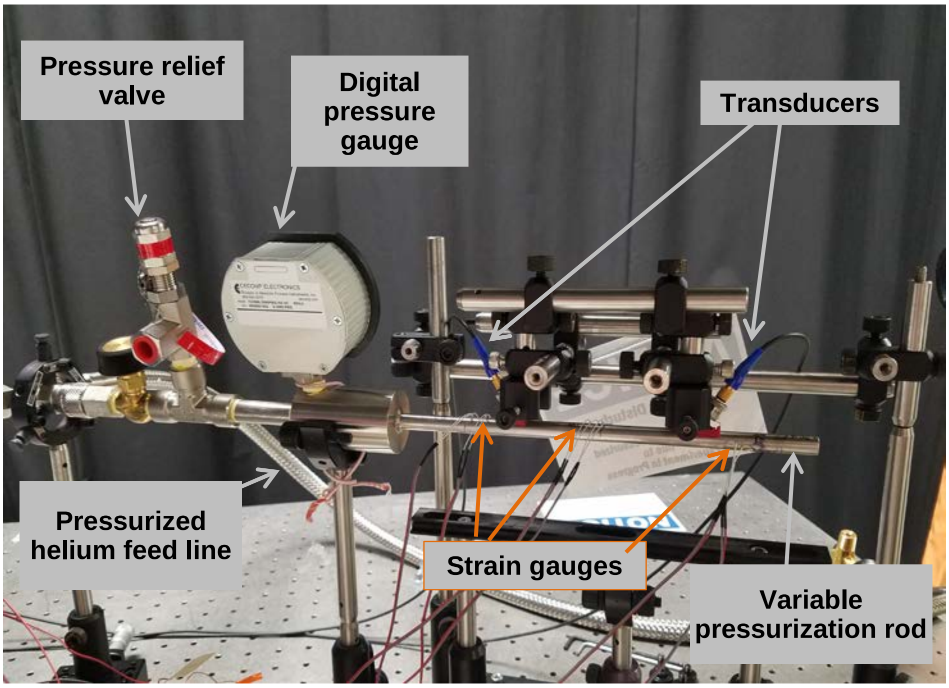

Fig. 3. The stainless steel variable pressurization rod included a pressure gauge and strain gauges. Pressure or vacuum is applied using a vacuum pump or compressed helium cylinder.

5. Results and Discussion

All of the pre-pressurized rods were tested and the fixed volume variable pressurization rod (without pellets/spring) was tested. Data adjustments for temperature compensation were not applied since the laboratory used to conduct the work was found to have a very stable room temperature. For the variable pressurization rod, the system was allowed to stabilize for a few minutes after changes in pressure before measurements were taken.

As shown in Fig. 4, the change in time of flight with sensor spacing was as expected, with more distance between the probes resulting in longer time of flight.

Figs. 5 and 6 present the results obtained with pre-pressurized Zirc-2 and Zirc-4 rods, respectively. Each rod was measured multiple times using a fixed sensor distance. A measurable change in time of flight with internal pressure differential was observed for the rods.

However, neither dataset produced the expected linear correlation of RIP and time of flight. Both the Zirc-2 and Zirc-4 datasets have a nonlinear appearance. While the Zirc-2 dataset always has an increase in time of flight with an increase in RIP as shown in Fig. 5, the Zirc-4 100 psig rod had a decreased time of flight from the 0 psig and 500 psig rod. The nonlinearities were consistently reproduced at different locations on the cladding, as shown in the Fig. 4 probe distance study, and, as discussed later, for other materials.

Given the discrete pressures available for the EPRI-provided test rods, it is difficult to come to a conclusion about the quality of any correlation that could be fit to the data. The Zirc-2 data demonstrates the expected increase in time of flight with increased pressure. The Zirc-4 data shows reductions in times of flight for the 50 and 100 psig rods, which were not expected.

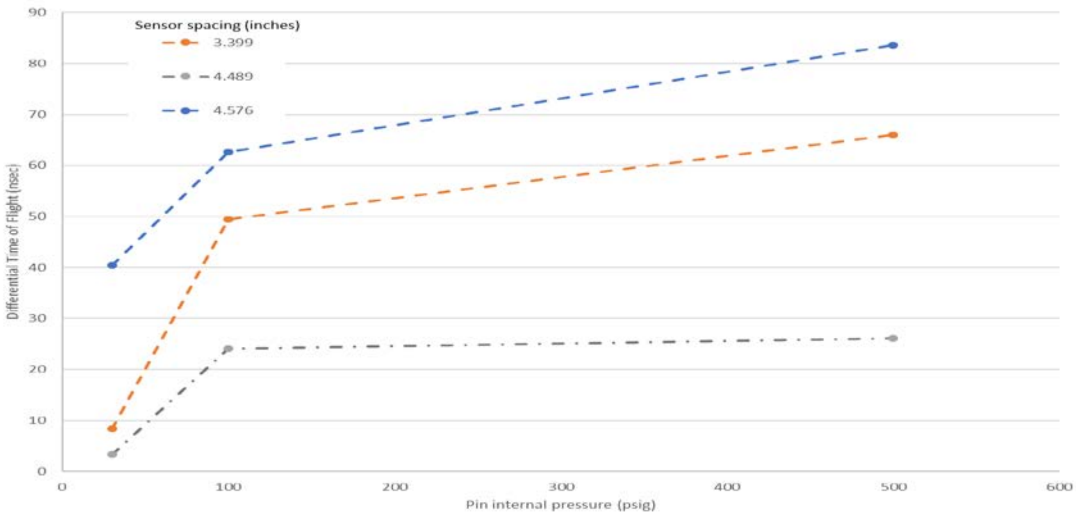

Fig. 4. Differential time of flight versus rod internal pressure of Zircaloy-2 (a typical boiling water reactor cladding alloy) pre-pressurized rods provided by EPRI with variable sensor spacing.

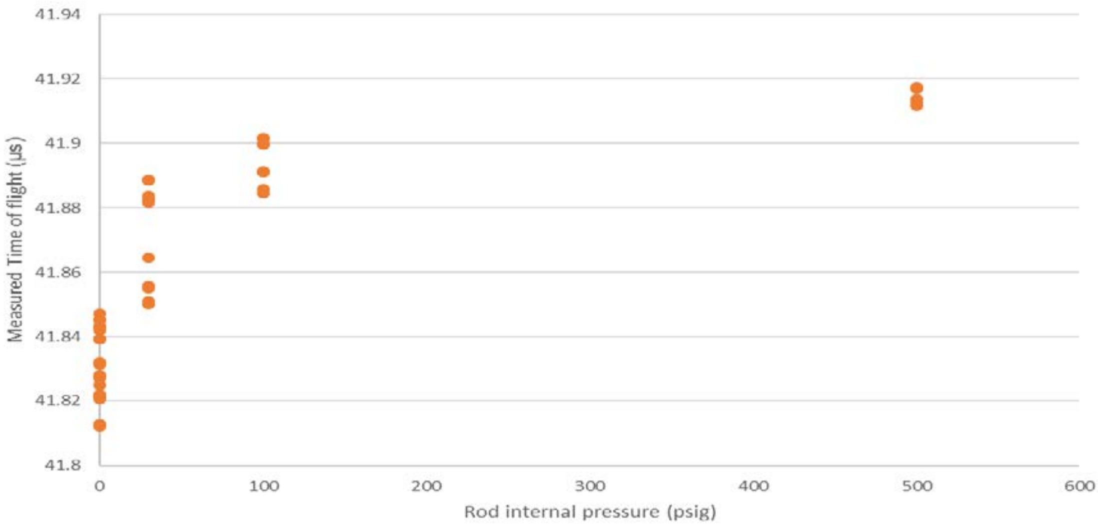

Fig. 5. Measured time of flight versus rod internal pressure of Zircaloy-2 (a typical boiling water reactor cladding alloy) pre-pressurized rods provided by EPRI.

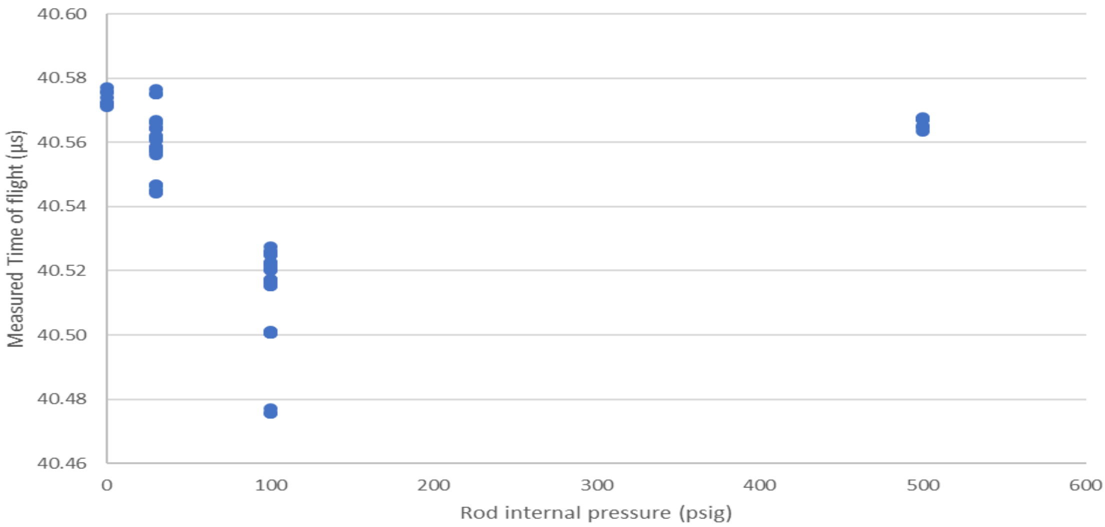

Fig. 6. Measured time of flight versus rod internal pressure of Zircaloy-4 (a typical PWR cladding alloy) pre-pressurized rods provided by EPRI.

The results for the pre-pressurized steel rods are shown in Fig. 7. While the 10-in.-long rods produced the expected linearly increasing time of flight with increased pressure, the other three rod lengths showed negative trends with pressure. Unfortunately, these rods were fabricated for another program, and details regarding the rod materials used are not available. The material used for the for 10-in. rods may have come from a different heat of material or perhaps even a different alloy from the other rods.

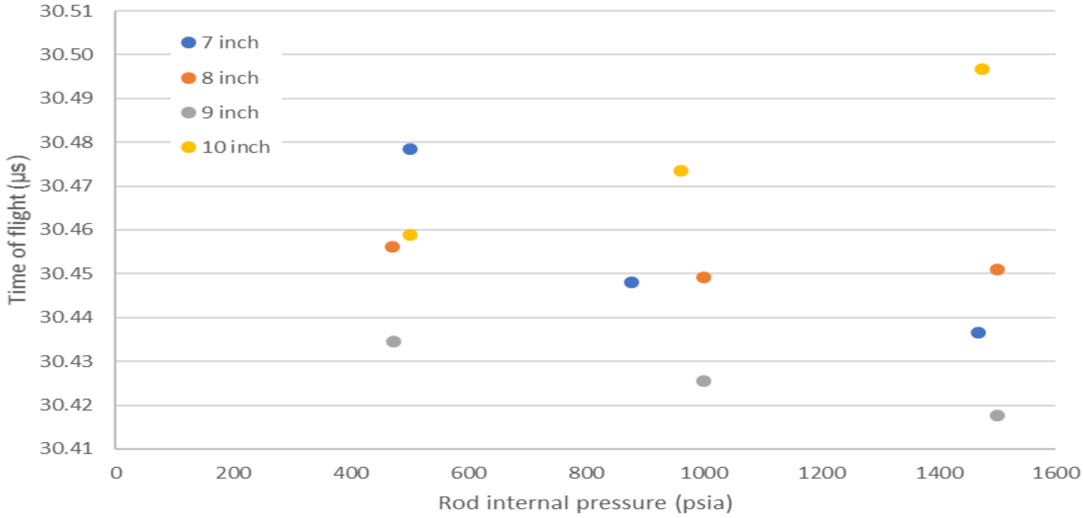

Fig. 7. Measured time of flight versus rod internal pressure for variable volume stainless steel pre-pressurized rods (four different rod volumes [7, 8, 9, and 10 in. long rods] at 500, 1,000, and 1,500 psia).

The pre-pressurized steel rods were also used to better understand the effects of different couplants. For the horizontal rod configurations in these tests, a short amount of hold time was needed after probe contact to allow the thickness of the couplant to stabilize. This is thought to be related to the fluid viscosity of the couplant and hold-down load applied to the probe. Different couplants did affect the measured time of flight, as shown in Fig. 8.

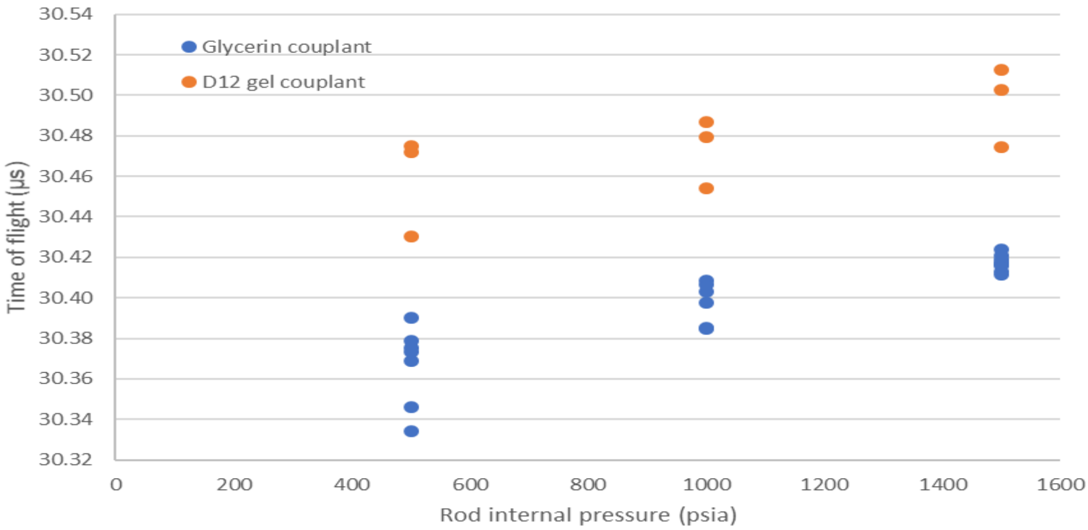

Fig. 8. Measured time of flight versus rod internal pressure of 10 in. long pre-pressurized stainless steel rods. The D12 gel couplant shifted the time of flight by ~0.1μs as compared with glycerin couplant.

The stainless steel variable pressure rod (without pellets/spring) was measured using a continuous pressure increase and decrease with a fixed sensor distance. The measured rod strain and time of flight are shown in Fig. 9. The time of flight nonlinearity observed with the reactor cladding materials using the pre-pressurized cladding samples was clearly evident on the stainless steel variable pressure rod. Additionally, a hysteresis was observed, with the pressure decrease sequence resulting in shorter times of flight than those observed for the pressure increase sequence. The material certifications for the variable rod samples are available, and finite-element modeling will be completed to better understand the sources of the nonlinearity and hysteresis.

A finite element analysis of the variable pressure rod was completed during its design to ensure that it was long enough to avoid any effects related to the end cap and weld stresses. This study, with the observation of the nonlinearities in all of the materials studied (some longer than others), leads us to believe that end effects are not relevant to this observation.

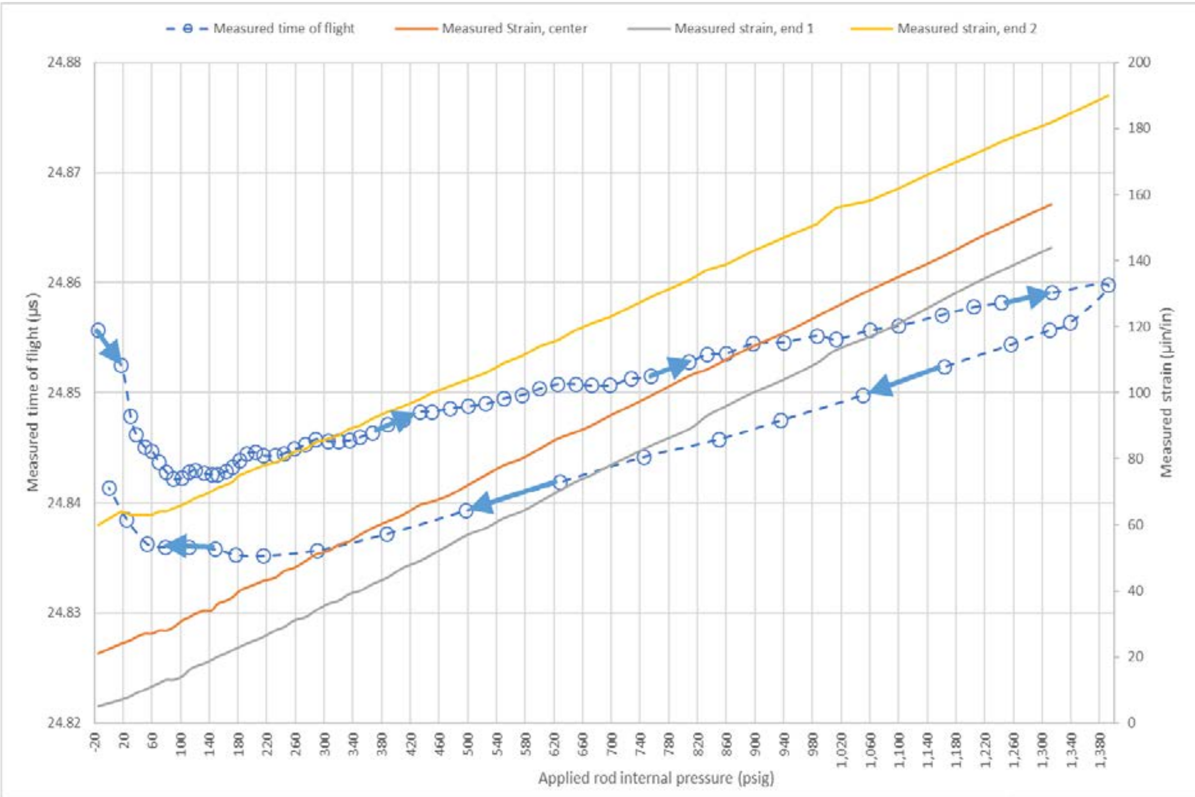

Fig. 9. Measured time of flight versus rod internal pressure of steel variable pressurization rod. This rod did not include simulated pellets or plenum spring. There is a clear and measurable response in time of flight with pressure. The nonlinearity at lower pressures needs to be investigated further.

6. Conclusions and Future Work

The proposed ORNL method offers a new approach to nondestructively measuring the internal pressure of SNF rods based on a fundamentally different pressure–time of flight relationship. The sound wave travels through a continuous solid medium, providing a simple path for the measurement. However, several unexpected results indicate a need for more development.

In the near term, the variable pressurization rod having pellets and spring will be measured with the existing fixturing, and this should provide some indication of the attenuation and reflections that can be expected for SNF rods. Also, finite-element modelling will be used to investigate the nonlinearities and hysteresis observed for the variable pressurization. The materials used to manufacture the pre-pressurized rods and the variable pressurization rods will be compared, to the extent possible. Since strain varies over the length of the rods, with the percentage change the greatest for low pressures, the pressure equation will be further evaluated for varying strain along the axial direction. Also, acoustic ray tracing methods may be used to investigate the observed nonlinearities.

In the future, measurements of SNF rods in ORNL's hot cells will be conducted. Several unpunctured as-discharged PWR SNF rods are available, and these rods are expected to be punctured to measure the rod internal pressure at a later date. The data obtained will be useful as a validation of the TAPS measurement configuration. The ultrasonic sensors are expected to be durable, even in the high-radiation field generated by SNF, but it is possible that the significant radiation background, sensor cable lengths, and remote-handling equipment could generate signal noise that would impact the quality of the data. Experiments conducted in the hot cell are expected to provide further proof of principle for the ultrasonic technique.

While the proposed TAPS measurement system is expected to provide a valid technique for nondestructive RIP measurement, there are parameters, such as the oxide layer, that may affect wave propagation in the cladding by introducing additional refraction and signal losses. Also, the measurement will be taken at the end of the fuel rod, where there may be a stress gradient in the cladding due to the end cap, and those effects must be accommodated.

7. References

[1.] *End-of-Life Rod Internal Pressures in Spent Pressurized Water Reactor Fuel.* EPRI, Palo Alto, CA: 2013. 3002001949.

[2.] Nuclear Energy Institute (2016). "Nuclear Cost in Context". Retrieved March 2016 from https://www.nei.org/CorporateSite/media/filefolder/Policy/Papers/Nuclear-Costs-in-Context.pdf?ext=.pdf.

[3.] Rosenkrantz, E. et al. (2009). Ultrasonic Method for Nuclear Fuel Rods Pressure and Gas Composition Released Measurement. First International Conference on Advancements in Nuclear Instrumentation Measurement Methods and Their Applications (ANIMMA), 2009. DOI: 10.1109/ANIMMA.2009.5503773.

[4.] Rosenkrantz, E. et al. (2009). Ultrasonic measurement of gas pressure and composition. Nuclear Instruments and Methods in Physics Research A 603 (2009) 504–509.

[5.] Gabr, F.AL et. al. (2003). Pressure and Composition of Gas Mixtures in Fuel Rods for Pressurised Water Reactors by an Ultrasonic Sensor. International conference on WWER fuel performance, modelling and experimental support, Varna (Bulgaria).

[6.] Stepinski, T. (2003). NDE of copper canisters for long term storage of spent nuclear fuel from the Swedish nuclear power plants. Conference on Nondestructive Detection and Measurement for Homeland Security, San Diego, CA.

[7.] Hughes, D.S. and Kelly, J.L. (1953). Second-Order Elastic Deformation of Solids. Phys. Rev. 92, 1145–1149.

[8.] Liu, W.H., et al. (1987). Shell Theory. Zhejiang University Press, p. 297.

[9.] Olympus-NDT (2011). Ultrasonic Transducers Technical Notes, Technical Report, Olympus NDT, Inc.

[10.] Chatzidakis S., et al. (2017). Sensor Requirements for Detection and Characterization of Stress Corrosion Cracking in Welded Stainless Steel Canisters. Proceedings of the ASME Pressure, Vessel & Piping Conference (ASME PVP 2017), Waikoloa, HA.