Nuclear Radiation Tolerance of Single Crystal Aluminum Nitride Ultrasonic Transducer

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Abstract

Ultrasonic technologies offer the potential for high accuracy and resolution in-pile measurement of a range of parameters, including geometry changes, temperature, crack initiation and growth, gas pressure and composition, and microstructural changes. Many Department of Energy-Office of Nuclear Energy (DOE-NE) programs are exploring the use of ultrasonic technologies to provide enhanced sensors for in-pile instrumentation during irradiation testing. For example, the ability of small diameter ultrasonic thermometers (UTs) to provide a temperature profile in candidate metallic and oxide fuel would provide much needed data for validating new fuel performance models, (Rempe et al 2011; Kazys et al, 2005). These efforts are limited by the lack of identified ultrasonic transducer materials capable of long term performance under irradiation test conditions. To address this need, the Pennsylvania State University (PSU) was awarded an Advanced Test Reactor National Scientific User Facility (ATR NSUF) project to evaluate the performance of promising magnetostrictive and piezoelectric transducers in the Massachusetts Institute of Technology Research Reactor (MITR) up to a fast fluence of at least $10^{21}$ n/cm$^2$. The irradiation is also supported by a multi-National Laboratory collaboration funded by the Nuclear Energy Enabling Technologies Advanced Sensors and Instrumentation (NEET ASI) program. The results from this irradiation, which started in February 2014, offer the potential to enable the development of novel radiation tolerant ultrasonic sensors for use in Material Testing Reactors (MTRs). As such, this test is an instrumented lead test and real-time transducer performance data is collected along with temperature and neutron and gamma flux data. Hence, results from this irradiation offer the potential to bridge the gap between proven out-of-pile ultrasonic techniques and in-pile deployment of ultrasonic sensors by acquiring the data necessary to demonstrate the performance of ultrasonic transducers. To date, very encouraging results have been attained as several transducers have continued to operate under irradiation. The irradiation is ongoing and will continue to approximately mid-2015.

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Peer-review under responsibility of the Scientific Committee of 2015 ICU Metz.
1. Background

The reactor insertion occurred on February 18, 2014 and we have been collecting data from the ultrasonic transducers on a daily basis. MIT reactor operator, David Carpenter, is responsible for uploading the data to a secure server every several weeks which PSU and INL have access to. PSU and INL are both collecting and analyzing the data independently and discussing the results as needed. The data include: pulse-echo A-scan’s collected from each piezoelectric and magnetostrictive transducer, voltage outputs from the self-powered neutron detector and self-powered gamma detector, reactor operating power, capsule temperature as measured by the two thermocouples, and neutron fluence. The following report presents the most current data available as well as recent analysis done to understand the performance of the sensors.

2. Environment

For this irradiation, the experiment capsule is positioned vertically within the in-core region of the ICSA near the top of the core in order to reduce heating and is held in place by two hollow titanium spacer capsules below. The ULTRA experiment is heated passively by the MIT reactor. The primary means for setting the experiment’s operating temperature is to balance the gamma and neutron heating of the components with heat rejection to the reactor primary water (50°C). The in-core facility used for this irradiation, the In-Core Sample Assembly (ICSA), consists of a titanium tube in contact with the reactor primary water on its outside surface. The internal space (about 5cm in diameter) is filled with an inert gas that is injected at a set mass flow rate at the bottom of the core and removed at the top. There have been several reactor SCRAM events as well as scheduled shutdowns. These events can be seen as dips in reactor power or constant lines in accumulated fluence. The MIT Research Reactor testing environment details are:

- Total Flux = 1.89E+14
  - Thermal Flux (<0.4 eV) = 2.12E+13 n/sq.cm
  - Epi-thermal flux (0.4 eV - 0.1 MeV) = 8.03E+13 n/sq.cm
  - Fast flux 1 (> 0.1 MeV) = 8.78E+13 n/sq.cm
  - Fast flux 2 (> 1.0 MeV) = 4.05E+13 n/sq.cm
- Gamma dose rate: 1 × 10⁹ r/hr
- Temperature: 400–500°C

3. Sample Preparation

In order to access the performance of the sensors during irradiation, a test capsule was designed to enable pulse-echo measurements. The design came from Parks and Tittmann’s work with high temperature transducers (Parks and Tittmann, 2014, Parks et al, 2013). Briefly, the sensor (AlN, BiT, ZnO) was coupled to a waveguide (Kovar or Aluminum 6061) using high purity gold or aluminum foil. A carbon-carbon backing was used to dampen the sensor vibrations, while a nickel plunger was used to increase pressure between the waveguide and the sensor material as well as to connect to the lead electrode. A stainless 304 casing was used as ground while a stainless 204 cap screwed into the casing and was used to exert pressure on the nickel plunger increasing the pressure between the sensor and the waveguide. A high temperature nickel-iron-cobalt spring was used to help maintain coupling pressure as temperature varied. See Fig. 1 for pictures during various stages of the assembly.

4. Pulse-Echo Measurements

INL was primarily responsible for characterizing the magnetostrictive transducer output. Therefore, this report will not include results from the magnetostrictive transducers except for when relevant to the piezoelectric
transducer performance. The two transducers (ZnO and AlN 1) output will not be reported here as they failed within the first several weeks of the experiment and their status has not changed. The following is data and analysis for the AlN 2 transducer. Data are collected from the sensor once every two hours.

Data are organized in a directory with each A-Scan residing in an independent file whose name corresponds to the time and date at which the data was collected. INL synthesizes the reactor sensor output data (elapsed time, temperature, etc.) which is saved in a separate file. A parsing program was written in MatLab to correlate the reactor environment variables to the A-Scan data collected. For each A-Scan, an FFT was calculated using a Hanning window of the first echo wave-packet. The amplitude of the fundamental frequency was used to measure the pulse-echo amplitude of the signal. Fig. 2 shows a plot of measured pulse-echo amplitude measured by the AlN transducer. The amplitude was normalized to the first measurement made at zero fluence. The data is compared to the data collected by Parks and Tittmann (2014).

Fig. 1. (a) The AlN transducer bonded to the Kovar waveguide. (b) The assembled sensor and capsule. The lead electrode is contacting the nickel plunger through direct contact and covered with an alumina sleeve. The alumina sleeve is fixed in place using Sauereisen. (c) A strain relief was design to ad support to the cable connections. (d) The full assembly laid out. (e) The assembled sensor.
5. Conclusions

For practical use in harsh radiation environments the selection criteria for piezoelectric materials for NDE and material characterization were summarized. Using these criteria piezoelectric Aluminum Nitride was shown to be a viable candidate (Reinhardt et al, 2014). The results of tests on an Aluminum Nitride based transducer operating in a nuclear reactor during a window of 18 months at a fast neutron flux of 4.05E+21 n/cm$^2$ and a gamma dose rate of $1 \times 10^9$ r/hr were presented. In all cases clear A-Scan measurements were made at the end of the power cycle. AlN seemed to maintain the initial transduction efficiency. The Aluminum nitride sensors pulse-echo amplitude varied by +/- 20%. The results show promise for utilizing both piezoelectric transducers in high neutron flux environments. The results offer potential for improving reactor safety and furthering the understanding of radiation effects on materials by enabling structural health monitoring and NDE in spite of the high levels of radiation and high temperatures known to destroy typical commercial ultrasonic transducers.

Acknowledgements

A portion of this research was supported by the U.S. Department of Energy, Office of Nuclear Energy under DOE Idaho Operations Office Contract DE-AC07-051D14517.

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