Optimizing Transmission of Acoustic Signals to Monitor Internal Conditions of Canisters for Dry Storage of Commercial Spent Nuclear Fuel[1]

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ABSTRACT

Safe storage of spent nuclear fuel (SNF) is critical to the nuclear fuel cycle and the future of nuclear energy. In the United States, SNF is stored primarily via two methods regulated by the U.S. Nuclear Regulatory Commission: wet storage in SNF pools and dry storage in dry cask storage systems (DCSSs). After about five years of cooling in spent fuel pools, the fuel assemblies are transferred into DCSSs, and the systems are filled with helium and sealed by welding. Deterioration of conditions inside of a DCSS is reflected in changes in the internal gas properties; this motivates the development of acoustic techniques to monitor internal gas properties, over extended storage periods, using sensors mounted on the exterior of the storage packages. However, a major challenge in collecting acoustic signals is the impedance mismatch between the steel canister shell and the gas. Only a small fraction of the ultrasonic signal can be transmitted through the gas medium. This paper documents experimental studies conducted on a full-scale canister mock-up to capture the gas-borne signals. Damping materials were pasted on the outside, and blocking and unblocking tests were conducted to identify the gas-borne signal. The results show that the excitation frequency plays an important role in maximizing the gas-borne signals. The gas-borne signal was successfully detected at around the theoretical time-of-flight. A high signal-to-noise ratio was achieved in the measurements. Next, the acoustic impedance matching layers were introduced, and the gas signal was drastically improved compared with that using no AIM layers.

Keywords: Spent nuclear fuel (SNF), Canisters, Internal conditions, Acoustic sensing

1. INTRODUCTION

The safe storage of spent nuclear fuel (SNF) following its removal from a reactor core is a crucial step in the nuclear fuel cycle. After around five years of cooling in spent fuel pools, SNF is loaded into SNF canisters for dry storage. These canisters are vacuum-dried, backfilled with helium, and sealed for interim storage. Assessing the internal condition of SNF canisters is essential after storage for multiple decades. However, their sealed nature and the difficulty associated with opening these packages for inspection make detecting internal conditions particularly challenging. Over the past few decades, several non-invasive approaches have been proposed and studied to assess the internal conditions of SNF canisters. These approaches include the use of dynamic testing [1][2], high-energy x-ray computed tomography [3], cosmic-ray muon tomography [4], and neutron imaging [5]. Acoustic methods are a promising solution for detecting

[1] This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (https://www.energy.gov/doe-public-access-plan).

abnormalities inside the canister. A non-invasive ultrasonic sensing technique that employs external ultrasonic transducers for detecting gas-borne signals was proposed in previous work by Meyer et al. [6]. Ultrasonic transducers are positioned on the canister's exterior, where a physical gap exists between the lid and the fuel basket. In this configuration, the ultrasonic excitation is coupled to the helium gas inside and is received by the receiver on the opposite side of the canister. Therefore, the resulting gas-borne signal contains the signature of the gas composition inside the canister and offers information about its internal conditions. Because sound speed differs for different gases, the time-of-flight (TOF) of the gas-borne signal varies in the presence of impurity gases [7]. However, the applicability of this method for sensing internal gas conditions on a full-scale canister mock-up remains unexplored. This challenging problem is addressed in this paper.

This study experimentally validates the proposed non-invasive sensing concept on a partial full-scale canister mock-up made from stainless-steel. The gas-borne signals were successfully detected by using damping materials and blocking and unblocking tests. Acoustic impedance matching (AIM) layers were applied to enhance the gas signals.

2. EXPERIMENTAL SETUP

Figure 1 illustrates the dimensions of the partial full-scale SNF canister mock-up at Pacific Northwest National Laboratory (PNNL). The mock-up is 1,524 mm in length and 1,715 mm in outer diameter. The shell thickness is 12.7 mm. The ultrasonic system comprised waveform generators, signal amplifiers, contact transducers, a preamplifier, filter, and an oscilloscope. The four channels from the waveform generators were synchronized. The first channel served as the trigger source and time baseline for the oscilloscope. The second channel was used to excite the main transducer after amplification via a 50 dB gain amplifier. The receiver picked up both the gas-borne signal and structural noise. The received signal was then amplified by a 60 dB gain provided by the pre-amplifier and filtered by a band-pass filter with a cut-off frequency ranging from 40 to 350 kHz and a gain of 20 dB. Finally, the received signal was recorded by the oscilloscope at a sampling rate of 1 MHz.
To mitigate structural noise, the outer surface was covered with damping materials. A foam board was used to block the gas path to isolate the structural noise.

Figure 1. Partial full-scale canister mock-up.

3. OPTIMIZATION OF EXCITATION FREQUENCY

The excitation frequency was determined by maximizing the transmission coefficient, α_t, between the steel and the gas (i.e., air in this case) within the canister. α_t can be calculated as [8]

$$\alpha_t = 1 \Big/ \sqrt{1 + 0.25\left(m - 1/m\right)^2 \sin^2\left(2\pi d/\lambda\right)} \tag{1}$$

where $m = Z_1/Z_2$. The variable Z_1 represents the acoustic impedance of the fluid, and Z_2 represents the acoustic impedance of the solid. Z_1 is equal to 4.3×10^{-4} MRayl for air. Z_2 is equal to 45.0 MRayl for stainless steel. d and λ represent the thickness of the steel plate and the wavelength of the transmitted wave, respectively. In this study, d is equal to 12.7 mm, which is the thickness of the canister shell, as mentioned previously.

The relationships between the transmission coefficient α_t and the parameter d/λ for the steel–air interface are illustrated in Figure 2. The ultrasonic signal transmission between the two materials is influenced by the wavelength and, thus, the excitation frequency. Peaks in the transmission coefficient α_t are observed in Figure 2 for the dimensionless quantity d/λ values of 0, 0.5, 1.0, 1.5, and 2.0.

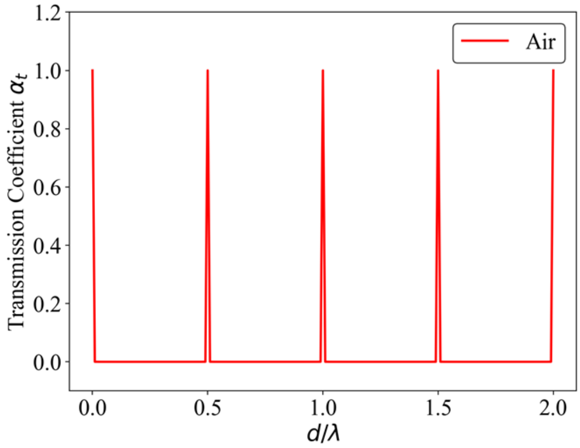

Figure 2. Relationship between α_t and d/λ of the steel-air and steel-water interfaces.

To optimize the signal transmission, a d/λ value of 0.5 was selected for this study. The wavelength λ was determined to be twice the thickness of the canister wall, or 25.4 mm. Therefore, the desired excitation frequency was determined to be

$$f = c_{steel} / \lambda = (5{,}800 / 25.4) \text{ kHz} = 228 \text{ kHz} \quad (2)$$

where c_{steel} is the longitudinal wave speed in steel (taken as 5,800 m/s). Therefore, the excitation frequency was taken as 225 kHz. The excitation was a 20-cycle sinusoidal burst with an amplitude of 800 mV_{p-p} from the waveform generator.

4. DETECTION OF GAS-BORNE SIGNALS

The blocked and unblocked signals were recorded, and their difference was calculated; results are shown in Figure 3. The blocked signal contains only structural noise, and the unblocked signal contains noise and gas signals. By taking the difference between the blocked and unblocked signal, the gas-borne signal can be clearly observed. The theoretical TOF of the gas-borne signal is 4,916 μs using a wave speed of 5,800 m/s in steel and 344 m/s in air at 20°C. The experimental TOF was obtained as 4,923 μs. This result demonstrated good agreement between theoretical and experimental results. The signal-to-noise ratio (SNR) was calculated as 1.73 dB.

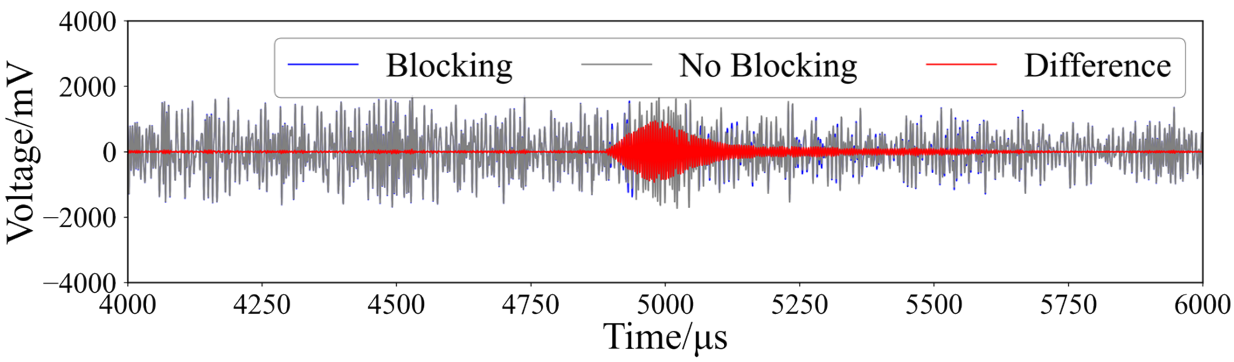

Figure 3. Gas-borne signal detection using single transmitter Tx and receiver Rx on the canister outside.

AIM layers were introduced to mitigate the impedance mismatch between the steel and air within the canister mock-up. Figure 4 illustrates the gas-borne signals obtained with and without AIM layers. When the AIM layers were applied solely on the Tx side, the peak–peak amplitude of the gas signal was increased by 63.0%, rising from 1500.5 to 2446.4 mV_{p-p}. When AIM layers were applied on both the Tx and Rx sides, the signal amplitude increased by 92.7% to 2891.1 mV_{p-p} compared with no AIM layers.

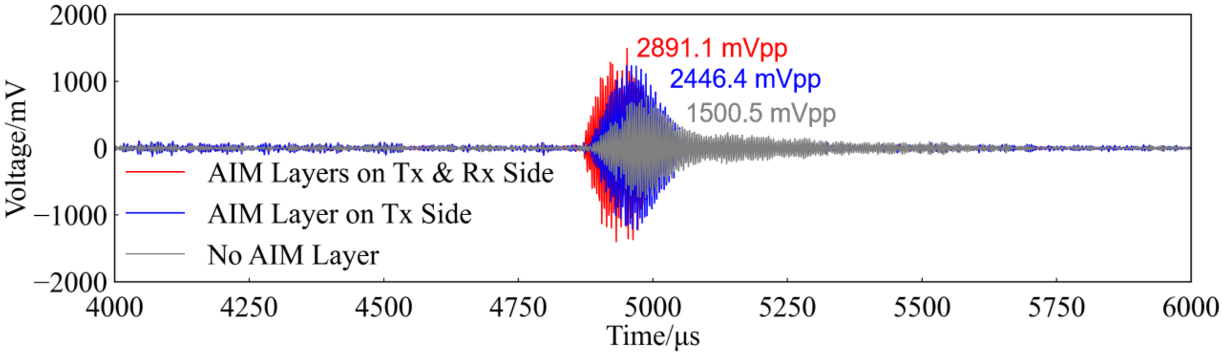

Figure 4. Effects of AIM layers on signal strength.

5. CONCLUSIONS

This study validated the acoustic sensing method on a partial full-scale canister mock-up. Ultrasonic testing was conducted to capture the gas-borne signals. The results showed that the excitation frequency plays an important role in maximizing the gas-borne signals. In this study, 225 kHz was found to maximize the gas-borne signals with a high SNR. The experimental TOF of gas-borne signal agreed well with the theoretical value. The AIM layers were introduced, and the gas signal amplitude was greatly improved by 92.7% compared to that obtained with no AIM layers.

ACKNOWLEDGMENTS

The funding for this research is provided by the U.S. Department of Energy under the Nuclear Energy University Program award no. DE-NE0009171. The findings and opinions presented here are those of the authors and do not necessarily reflect the views of or endorsed by the sponsor.

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