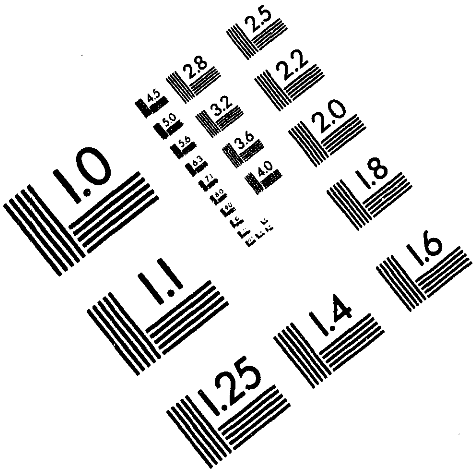

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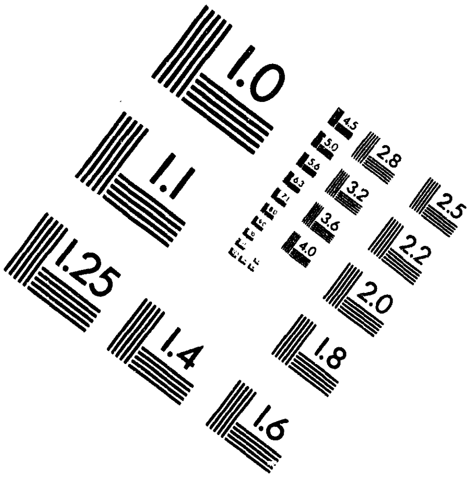

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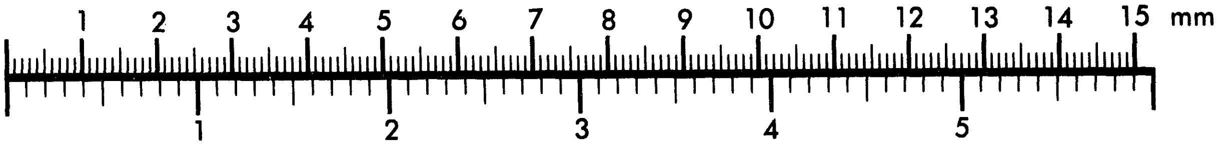

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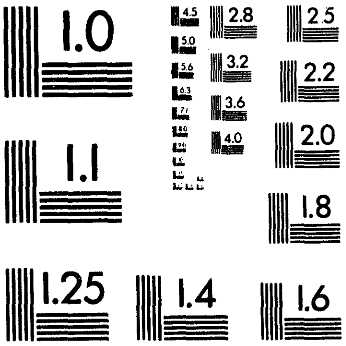

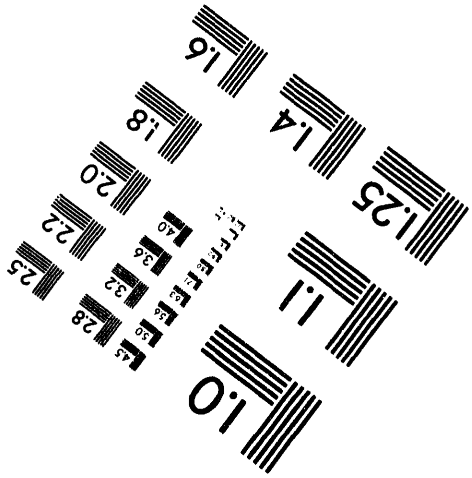

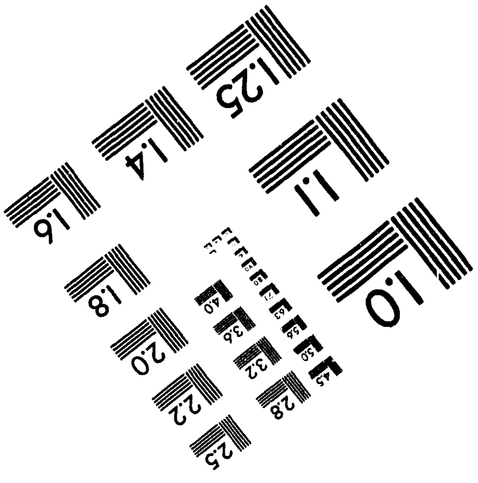

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# NON-DESTRUCTIVE EVALUATION OF NUCLEAR MATERIAL STORAGE CONTAINER INTEGRITY USING AN ACOUSTIC TECHNIQUE

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## ABSTRACT

A non-intrusive method for determining the gas mixture in a sealed container using acoustics has been conceived. Analysis has shown that it is possible to both excite the acoustic resonance of the gas cavity, and detect when resonance occurs from the outside surface of the container. The resonant frequency of the acoustic cavity is dependent on the molecular weight of the gas that fills it. A change in the mixture of gases within the cavity alters the gas molecular weight and can produce a detectable change in the resonant frequency of the cavity. This concept provides a method of monitoring and/or analyzing the gas mixture in a sealed container without taking physical samples. An advantage of this technique is that it eliminates safety and contamination risks associated with breaching a pressure boundary and taking a sample of potentially hazardous gases in order to monitor or analyze the mixture.

## INTRODUCTION

The impetus for this concept arose from a requirement that sealed nuclear material long-term storage containers be safe to open should the need arise. Typically, the nuclear material is kept in a sealed inner container and is covered by an inert gas such as Argon. Double containment is provided by a welded outer shell with a cover gas such as Helium between the containers. If, through corrosion or some other mechanism, the inner container is breached, radioactive material—and the argon cover gas with it—would pass into the volume between the inner and outer containers. This failure would not be apparent from outside the storage container. If the outer shell of the faulty container were opened, the potential for worker radioactive contamination and exposure exists. A method for determining whether the inner container is breached before opening the outer container is required.

One method currently used is to take a sample of the Helium cover gas between the inner and outer containers and analyze it using mass spectrometry. If the inner container is breached, Argon from the inner container will diffuse into the Helium and be detected, indicating inner container failure. The acoustic method described in this paper does not require breaching the pressure boundary and physically sampling the gas. Only contact with the outer surface of the outer container is required.

Though this study was performed for the specific application of nuclear material storage, there are other circumstances where it might prove useful. The requisite equipment for applying this technique is relatively inexpensive and simple to use. There are limitations, however, this paper describes the anticipated advantages and difficulties with this method.

## The Theoretical Background

In an enclosed volume, reflected sound waves of certain wavelengths are superimposed causing an increase of the sound pressure at the boundaries. This condition is called resonance or a standing wave and it occurs when the sound wavelength is half of an even multiple of an enclosure dimension. The normal modes are the associated wave patterns and the eigenfrequencies are the sound frequencies at which resonance occurs. This study focuses on the first or second resonant modes because, in general, higher sound pressures occur at the lower modes making them easier to detect. In addition, it is necessary to clearly distinguish between the acoustic resonance and the higher frequency structural modes.

The sound speed in an ideal gas is described as (Kinsler et al, 1982)

$$c = \sqrt{\gamma R T} = \sqrt{\frac{\gamma R_u T}{M}} \qquad (1)$$

Where:
c = sound speed (m/s)
$\gamma$ = ratio of specific heats (unitless)
R = gas constant {N·m/(kg·K)}
$R_u$ = universal gas constant {8.31434 J/(mol·K)}
M = molecular mass of the gas (kg/mole)
T = absolute temperature (K)

The resonant frequenct of an acoustic cavity is described by equation (2).

$$f=\frac{c}{K}=\frac{\sqrt{\gamma R_u T}}{K\sqrt{M}} \qquad (2)$$

Where:
f = the resonant frequency of the acoustic cavity (Hz)
K = a geometric factor (length)

In terms of gas density, equation (3) shows a second order dependence on the measured resonant frequency.

$$M=\frac{\gamma R_u T}{K^2 f^2} \qquad (3)$$

Sound pressure is typically extremely small relative to atmospheric pressure. The sound pressure corresponding to a relatively loud pure tone of 90-dB is less than $^1/_{100,000}$ of atmospheric pressure (Wilson, 1989). It is anticipated, then, that the structural vibrations of the outer container due to sound pressure of the acoustic cavity at resonance will be very small and challenging to detect. Likewise, exciting the acoustic resonance through the outer container presents similar difficulties. The large impedance mismatch between the metal and gas means that energy is not well coupled—most of it is reflected in the form of reflected waves at the metal/gas interface.

## THE PREDICTED RESPONSE

Finite element analysis was used to estimate the magnitude of the structural response due to internal acoustic resonance and the ability to excite that resonance externally. Selection of the appropriate transducers for detection of acoustic resonance required a degree of understanding of the response of the system.

### Model Description

Figure 1 shows a clipped, three dimensional finite element model of an outer container (black) and the gas filled space between the container shells (gray). The finite element code ABAQUS v5.3 was used to used to determine the structural vibration as well as acoustic modes (HKS, 1994).

Second order, reduced integration structural elements (S8R5) were used to model the shell. Twenty noded solid acoustic elements (AC3D20) were used to simulate the gas cavity with two elements through the annular thickness. The coupled acoustic-structural response was simulated by including acoustic interface elements (ASI8) and exciting various structural nodes at a constant force over a range of frequencies. Acoustic interface elements couple sound pressure in the cavity to the nodal forces in the shell structure. The inner container was not simulated and assumed to be perfectly acoustically hard in this case. A periodic 0.89 N (0.2 lb) force was applied at various single node locations over the frequency range of interest using the *STEADY STATE RESPONSE option in ABAQUS. This simulates the loading of commercially available electromagnetic shakers. Table 1 describes the simulated container details. This simplified geometry was intended as a first effort at understanding the physics involved and is not representative of currently used storage containers. Features such as internal connections and external fitting were neglected for simplicity.

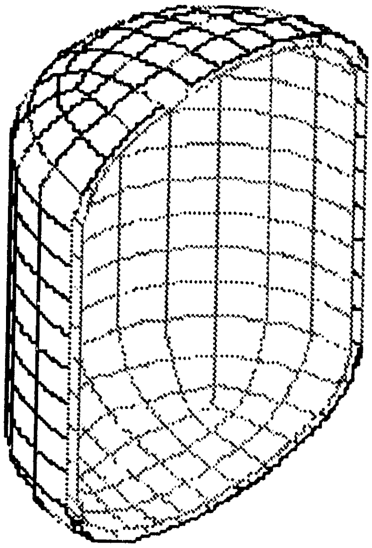

FIGURE 1. FINITE ELEMENT MODEL OF CONTAINER

TABLE 1. EXAMPLE CONTAINER CHARACTERISTICS

| CONTAINER FEATURE | |
|---|---|
| Diameter | 14" OD |
| Wall Thickness | 0.188" |
| Total Height | 18" |
| Top and Bottom | 2-to-1 ellipsoid caps |
| Cavity Annular Thickness | 0.5" |
| Materials (Shell/Gas) | 304 SS/Ar or He |

### Analysis Results

Table 2 lists the important eigenfrequencies for this system. These were calculated using the finite element models. The acoustic and structural modes were calculated separately. The first acoustic mode is the longitudinal mode (cap-to-cap) and the second mode is the lateral mode (side-to-side). The structural modes are more complex. The first structural mode is a lateral breathing mode at 949 Hz. There are multiple other breathing modes before the first longitudinal, non-breathing mode at 2206 Hz.

TABLE 2. PERTINENT EIGENFREQUENCIES

| MODES OF VIBRATION (Hz) | |
|---|---|
| 1st Structural (breathing) | 949 |
| 1st Structural (longitudinal) | 2206 |
| 1st Acoustic-Ar (longitudinal) | 319 |
| 1st Acoustic-He (longitudinal) | 1009 |
| 2nd Acoustic-Ar (lateral) | 364 |
| 2nd Acoustic-He (lateral) | 1150 |

Figure 2 shows the locations on the shell where excitation and/or measurements are reported. Points 1 and 3 were chosen to excite the first (hence lowest frequency) acoustic mode. Points 2 and 4 were chosen because is the region of lowest structural stiffness. This should allow more displacement for the given force resulting in increased coupling between the gas and shell. No material damping was used in this analysis.

Figures 3 through 6 show the predicted acceleration of points on the shell near acoustic resonance frequencies.

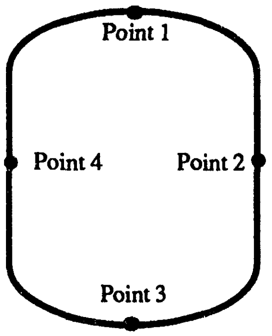

FIGURE 2. MEASUREMENT/EXCITATION LOCATIONS

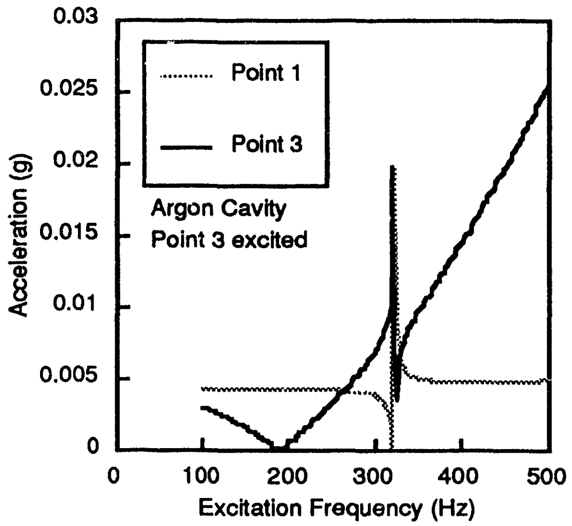

FIGURE 3. FIRST ACOUSTIC MODE-ARGON

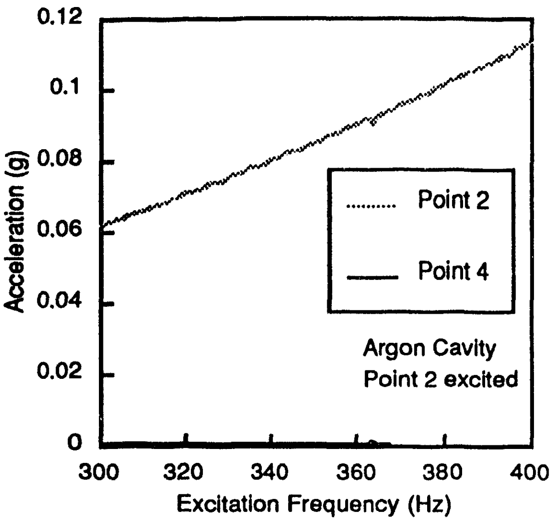

FIGURE 4. SECOND ACOUSTIC MODE-ARGON

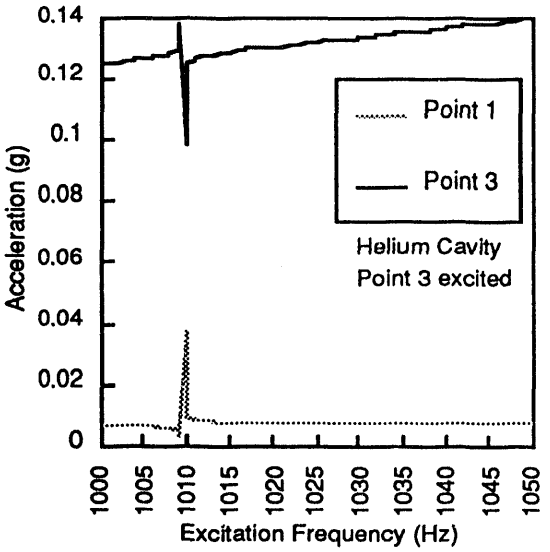

FIGURE 5. FIRST ACOUSTIC MODE-HELIUM

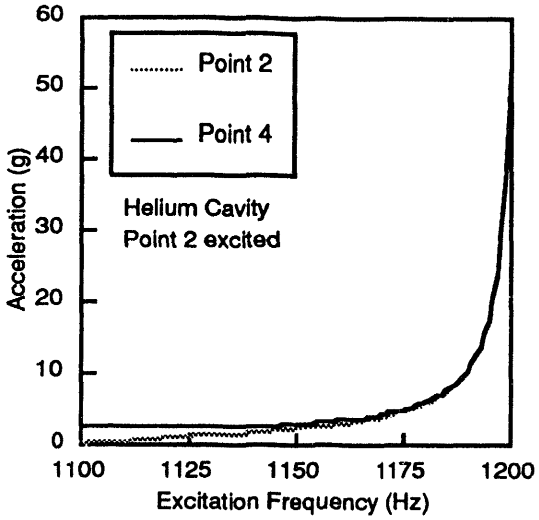

FIGURE 6. SECOND ACOUSTIC MODE- HELIUM

The finite element results show that small acceleration spikes of the shell are expected when excitation at the acoustic cavity resonance occurs. These spikes are typically on the order of $^{1}/_{100}$ g. The spikes are approximately of the same magnitude whether they are at the point of excitation or on the opposite antinode. A substantial difference in the mean acceleration near acoustic resonance is calculated—the point of excitation typically having a much higher acceleration due to the loading. This suggests that, if transducer sensitivity is important in this acceleration range, measurement at the non-excited antinode would yield the highest gain. The absolute magnitude of the acceleration is not important with this technique. As long as the acceleration spike is detectable, the frequency at which the spike is observed is the critical feature.

Excitation of the lateral or second mode was shown to be less effective that the longitudinal or first mode. Also, the effect of the structural mode is observed in Figure 6. The spike near 1200 Hz is a structural breathing mode and has associated acceleration values that are orders of magnitude higher than those due to acoustic resonance. This is not unexpected due to the large impedance mismatch between the steel and gas. In Figure 6, the acceleration spike of magnitude $1x10^{-3}$ g at 1150 Hz due to acoustic resonance is indistinguishable compared to the approximately 3 g acceleration of the structure in the vicinity of the 1200 Hz structural resonance.

## CONCLUSIONS

This analysis shows that it should be possible to both excite the acoustic resonance of a cavity and detect when resonance occurs from the outside surface of the container that encloses it. The resonant frequency of the cavity is a function of the molecular weight of the gas that fills it. If the gas mixture in the cavity changes, the resonant frequency will shift accordingly. One implication is that, with further development, this method might prove useful for the storage of hazardous material that requires double containment. If the inner containment fails, the cover gas along with the material can escape into the secondary containment. If a different density cover gas is used between the two containment vessels, the mixing of the gases will cause a detectable shift in the acoustic resonance frequency of the cavity.

Small acceleration spikes at the resonant frequency of the cavity are calculated in this analysis for the sample configuration. These spikes are on the order of $^{1}/_{100}$ g. Accelerometers are available that are capable of detecting this magnitude acceleration in the frequency range of interest.

There are two major advantages of this technique. The non-intrusive nature of the testing eliminates the potential for exposure to the contained material. Secondly, the entire system to detect acoustic cavity resonance could be simply comprised of: an appropriate accelerometer, an electromagnetic shaker to excite the container and a computer based analyzer. The major limitation of this technique would likely be the special geometric requirements of the containment design. It is necessary that acoustic resonant frequencies be well distinct—preferably much lower than—the structural resonance frequencies.

## ACKNOWLEDGMENTS

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