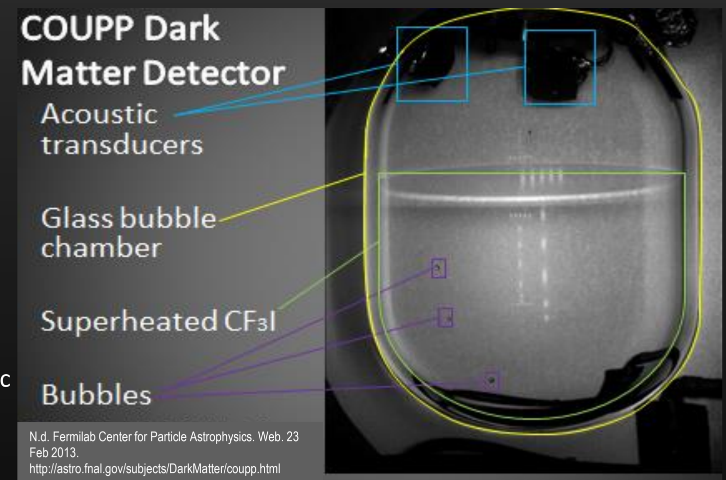
Making a Matching Layer for Acoustic Sensors

for a COUPP Dark Matter Detector

INTRODUCTION

Although the existence of dark matter is supported by a variety of strong observational evidence, very little is known about its nature. Several plausible dark matter candidates have been proposed, but their weak interactivity with normal matter makes them extremely difficult to detect. For this reason, the only known way to directly detect dark matter is to detect nuclei scattered by dark matter, ruling out all other possible sources of nuclear recoils.

The COUPP experiment (Chicagoland Observatory for Underground Particle Physics) at Fermilab employs bubble formation as a means to detect dark matter and uses super-heated liquid CF_3I as a target for the collisions. The CF_3I is located in a quartz bell jar in a pressure vessel surrounded by propylene glycol, and the kinetic energy transfer in the collisions causes bubbles to form in the CF_3I. These bubbles result in acoustic emissions which can be analyzed to discern the types particles involved in the collisions.



COUPP uses lead zirconate titanate (PZT) piezoelectric acoustic transducers (sensors which convert acoustic waves into electronic waves and vice versa) epoxied to the exterior of the quartz jar containing the CF_3I to record bubbles' acoustic emissions, and they have been able to discriminate over 99.3% of the alpha contamination. However, as COUPP detectors grow larger (COUPP aims to increase its sensitivity with a 500 kilogram detector), the acoustic sensors themselves become potential sources of background radiation (their PZT coating is a source of neutron emissions), so the number of acoustic sensors must be minimized. This can be done by maximizing transducer sensitivity so fewer are needed for discrimination.

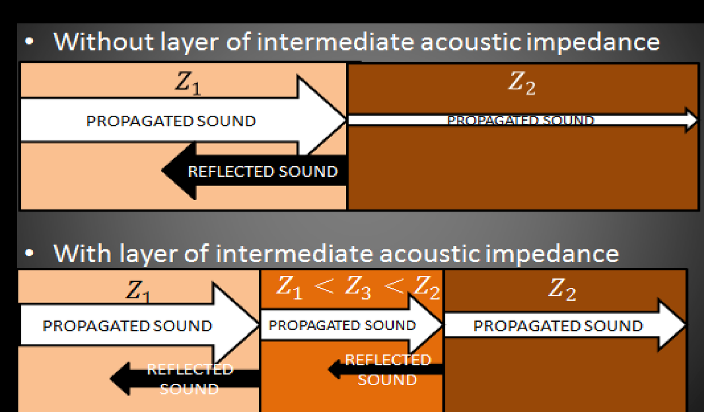
One factor limiting the acoustic sensor sensitivity is a significant difference in acoustic impedance between the fused silica quartz and the PZT manufactured by Virginia Tech: the quartz has an acoustic impedance of 13 MRayl, while the PZT has an acoustic impedance of 18 MRayl. This mismatch causes much of the sound wave to be reflected rather than transmitted to the PZT transducers, since the percent reflection from a medium of acoustic impedance Z_1 to a medium with acoustic impedance Z_2 is given by

$$R_{12} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

To decrease the percent reflection, a material with a strategically chosen acoustic impedance Z_3 can be placed between the two media. The total percent reflection across both barriers is then given by

$$R_{total} = R_{13} + R_{32} - R_{13}R_{32}$$

and is minimized when the acoustic impedance of the intermediate layer is $Z_3 = \sqrt{Z_1 Z_2}$, the geometric mean of the acoustic impedances of the surrounding media.



Minimizing the percent reflection will result in the maximum percent propagation, leading to maximum sensitivity. Therefore, in order to maximize the sensitivity of the transducers, a material with acoustic impedance equal to the geometric mean of the acoustic impedance of the quartz and that of the PZT can be placed between the quartz and transducer so that less reflection occurs and more of the signal is able to travel to the transducers.

HYPOTHESIS

COUPP's acoustic sensors can be improved with a tungsten powder and epoxy composite matching layer of optimal acoustic impedance and thickness.

PROCEDURE

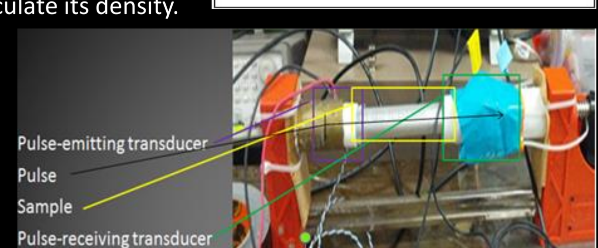
1. Test samples of varying percent tungsten carbide were made.

This is a photograph of the epoxy resin, epoxy hardener, and tungsten powder which are about to be mixed and poured into the molds.

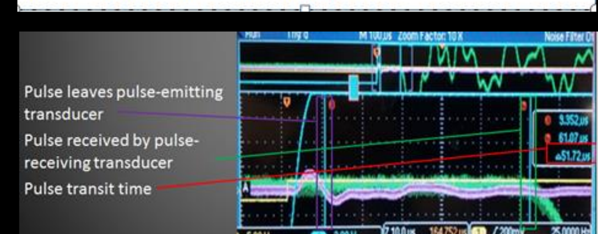
A. Molds were created and correct masses of epoxy hardener, epoxy mixture, and tungsten carbide powder were measured.
B. Dissolved air was removed using a bell jar evacuation chamber.
C. The tungsten powder, resin, and hardener were thoroughly stirred
D. Molds were filled and clamped into a custom-made rotator so that the tungsten powder would not settle during the hardening time.
E. When the samples had hardened, the edges of each sample were buffed.

This is a photograph of the custom-made rotator used to keep the tungsten powder uniformly dispersed while the sample hardened.

2. The acoustic impedances of the test samples were calculated.
A. Each sample's mass and volume were measured using a scale and water displacement method.
B. Each sample's mass was divided by its volume to calculate its density.
C. The transit time of sound through each sample was measured with an oscilloscope and a custom made "sono clamp," a clamp which had a pulse-emitting transducer at one end and apulse-receiving transducer at the other end. The sono clamp was first tested with an aluminum sample with a known speed of sound to make sure it was working properly.
D. The sample's length was measured and divided by the sample's time interval to calculate the speed of sound through the sample.
E. Each sample's density was multiplied by its speed of sound to obtain its acoustic impedance



This photograph shows the setup of the "Sono clamp," which was used to measure the transit time of sound through a sample.



This photograph shows the display on the oscilloscope connected to the "Sono clamp."

3. The data was converted from percent tungsten carbide by mass to percent tungsten carbide by volume using the equation

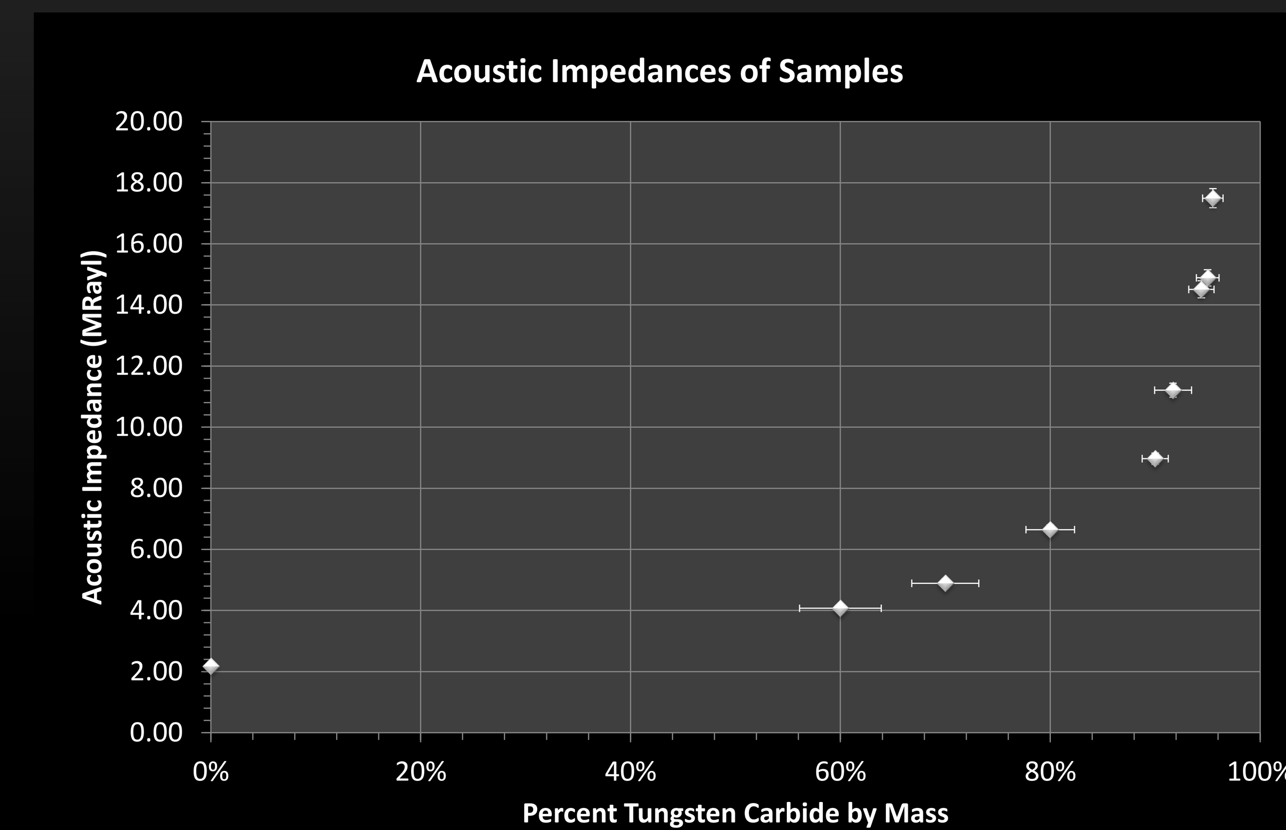
$$\chi_v = \frac{1.1\chi_m}{15.8 - 14.7\chi_m}$$

(Continued on top right)

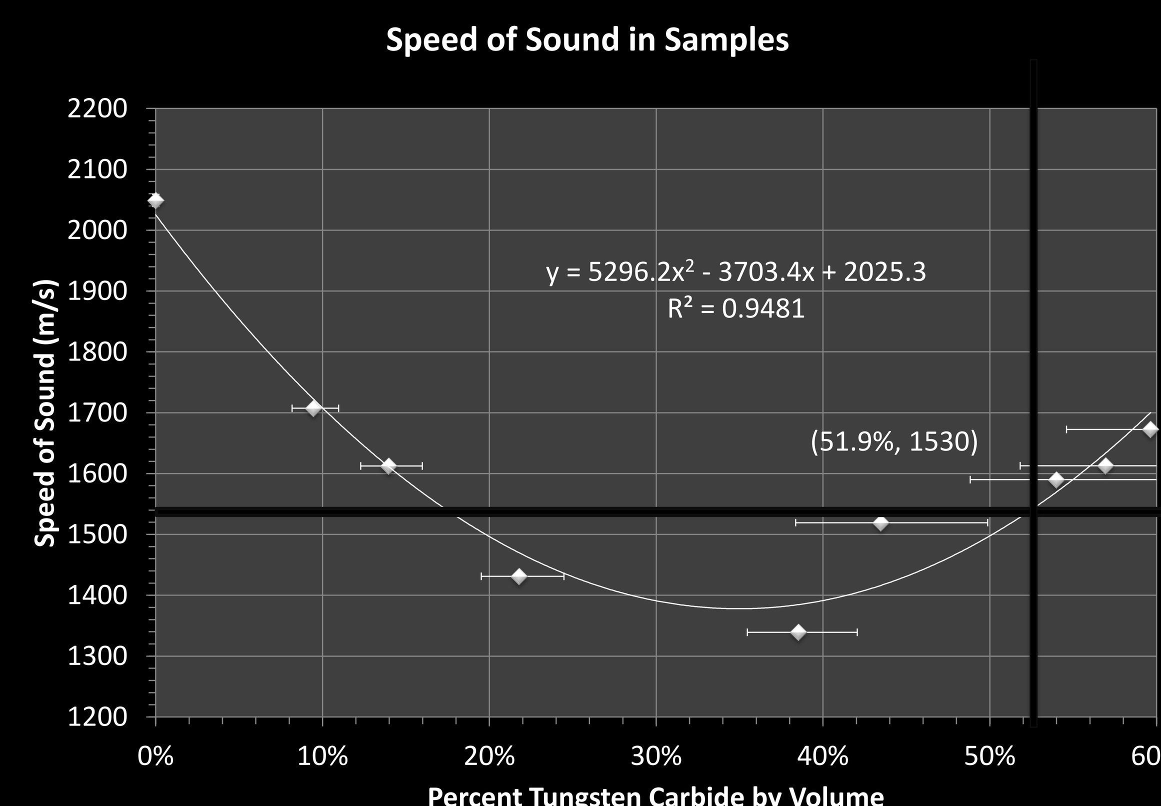
DATA

Percent Tungsten Carbide by Mass	Percent Tungsten Carbide by Volume	Density of Sample $\frac{\text{avg mass}}{\text{displ.volume}} * \frac{kg}{10^3 g} * \left(\frac{m}{10^2 cm}\right)^3$	Speed of Sound Through Sample $\frac{\text{length}}{\text{time}} * \frac{\text{m}}{10^2\text{cm}} * \frac{10^6\mu\text{s}}{\text{s}}$	Acoustic Impedance $(\text{density}) * (\text{speed}) \left(\frac{\text{Rayl}}{\frac{\text{kg}}{\text{m}^2\text{s}}}\right) * \left(\frac{\text{MRayl}}{10^6\text{Rayl}}\right)$
0%	0%	1.06 x10^3 kg/m^3	2049 ±10 m/s	2.18 ±0.13 MRayl
60 ±4%	9.5 ±1.5%	2.39 x10^3 kg/m^3	1707 ±7 m/s	4.07 ±0.13 MRayl
70 ±3%	14.0 ±2.0%	3.03 x10^3 kg/m^3	1612 ±6 m/s	4.89 ±0.14 MRayl
80.0 ±2.3%	21.8 ±2.7%	4.64 x10^3 kg/m^3	1431 ±5 m/s	6.65 ±0.16 MRayl
90.0 ±1.2%	38.5 ±3.5%	6.70 x10^3 kg/m^3	1339 ±5 m/s	8.97 ±0.18 MRayl
91.7 ±1.8%	43.5 ±6.4%	7.38 x10^3 kg/m^3	1519 ±6 m/s	11.2 ±0.23 MRayl
94.4 ±1.2%	54.0 ±6.2%	9.13 x10^3 kg/m^3	1590 ±6 m/s	14.5 ±0.28 MRayl
95.0 ±1.1%	56.9 ±6.1%	9.23 x10^3 kg/m^3	1613 ±6 m/s	14.9 ±0.27 MRayl
95.5 ±1.0%	59.6 ±5.9%	10.5 x10^3 kg/m^3	1673 ±7 m/s	17.5 ±0.31 MRayl

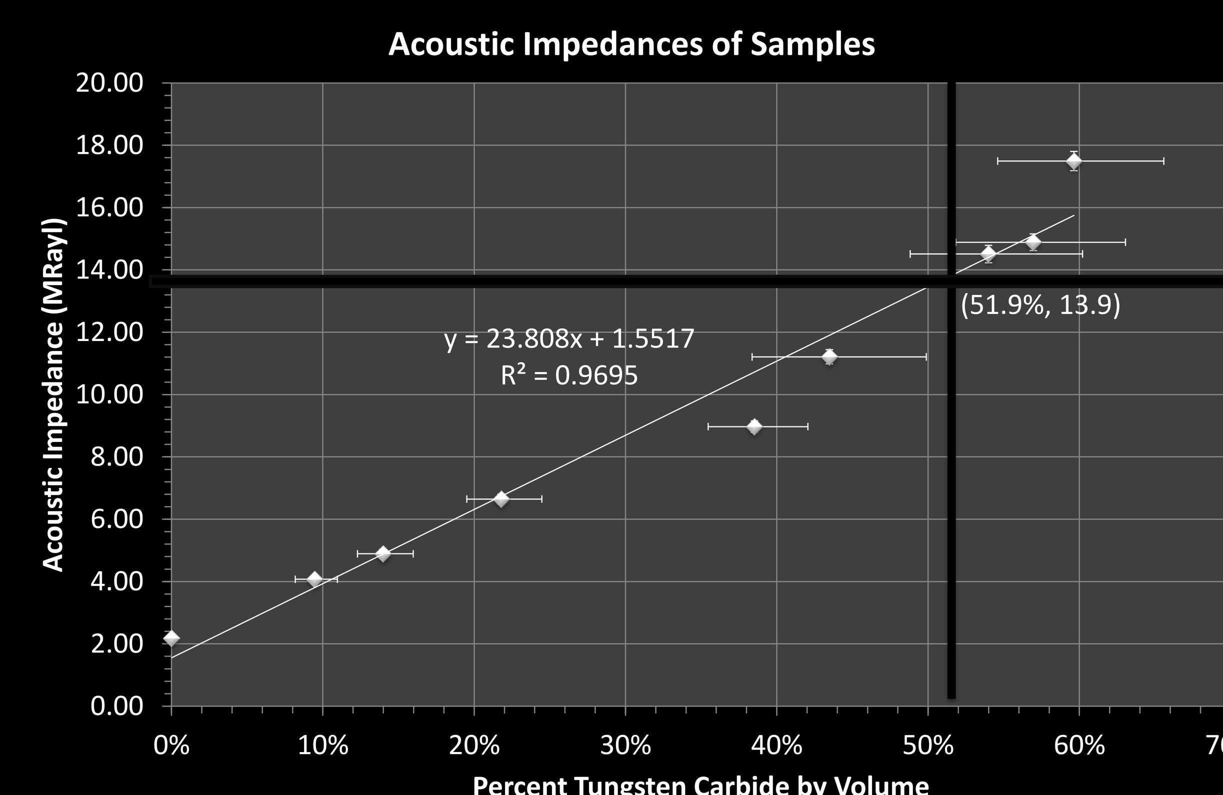
Table 1: Percent tungsten carbide by mass and volume, density, speed of sound, and acoustic impedance of each sample



Graph 1: Acoustic impedance vs. percent tungsten carbide by mass for each sample



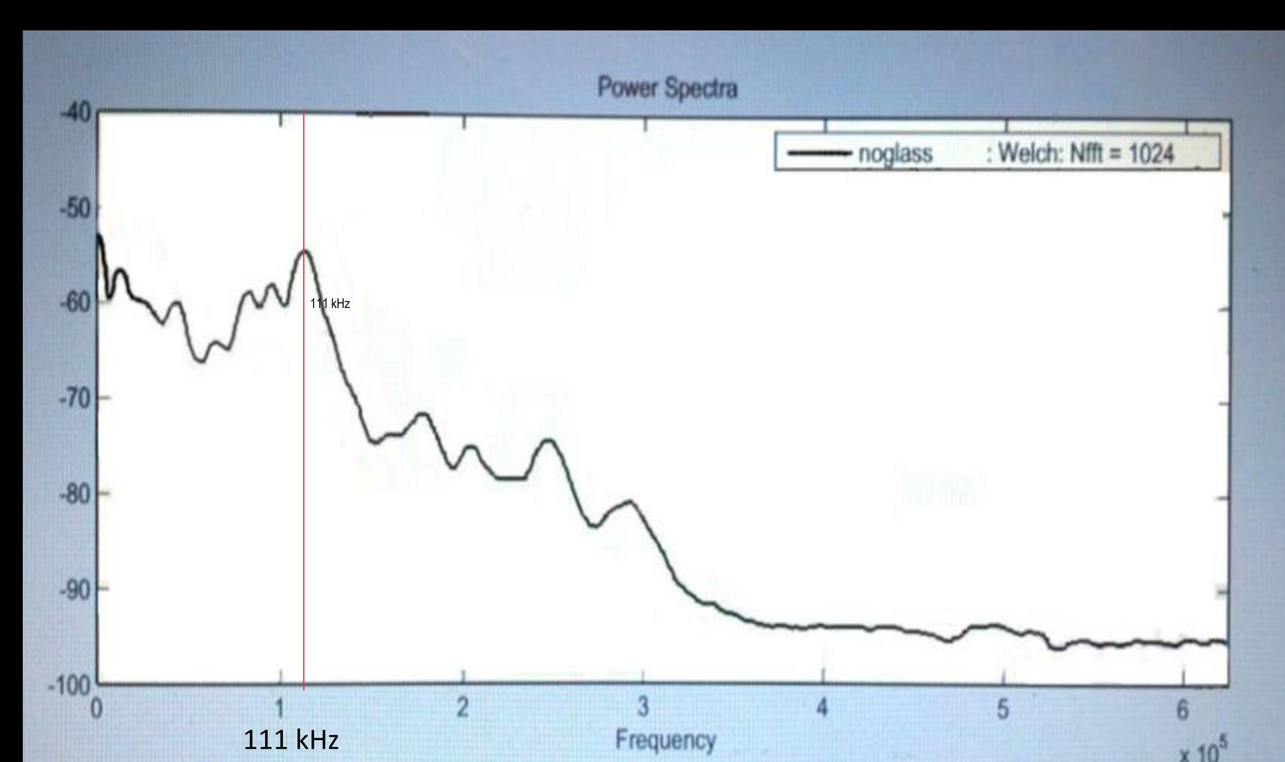
Graph 2: Speed of sound vs. percent tungsten carbide by volume for each sample



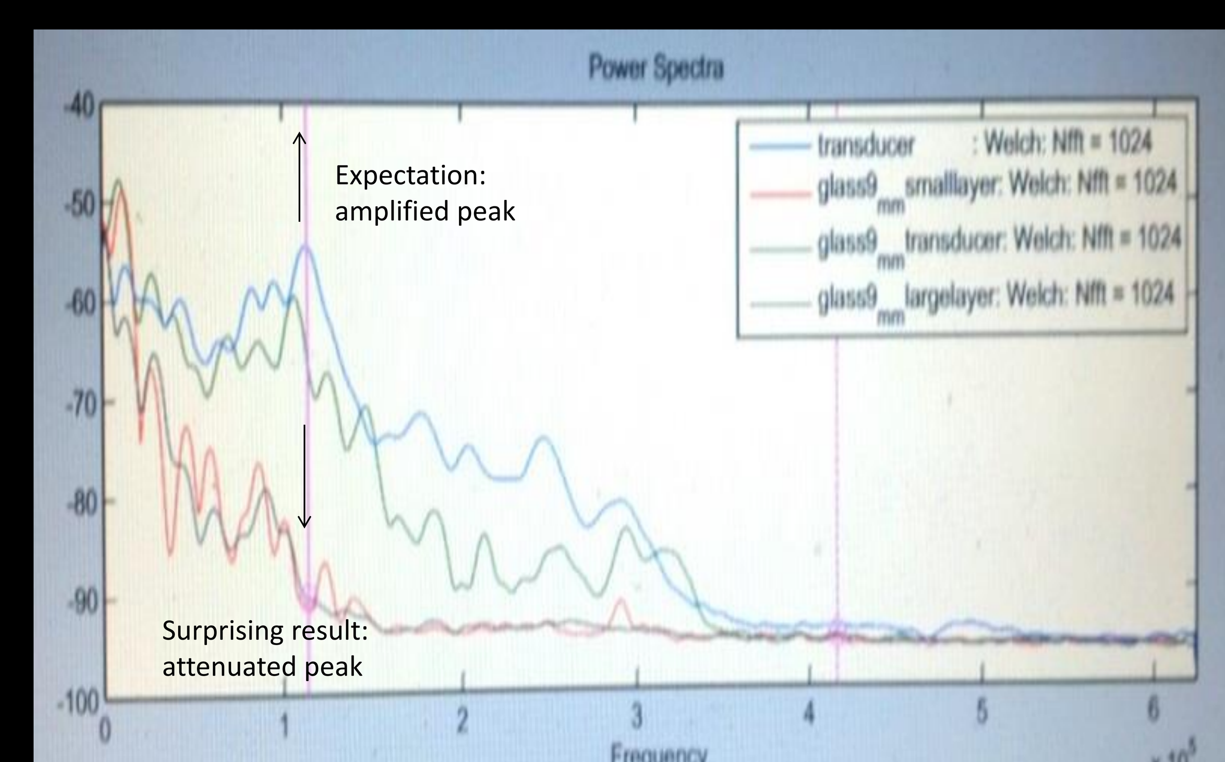
Graph 3: Acoustic impedance vs. percent tungsten carbide by mass for each sample

Calculated Quantity	Calculation	Result
Goal thickness	$\frac{\lambda}{4} = \frac{1}{4} * \frac{\text{speed of sound in sample}}{\text{bubble sound frequency=transducer peak frequency}} = \frac{1}{4} * \frac{1530 \text{ m/s}}{111 \text{ kHz}}$	3.4 mm

Table 2: Matching layer goal thickness calculation

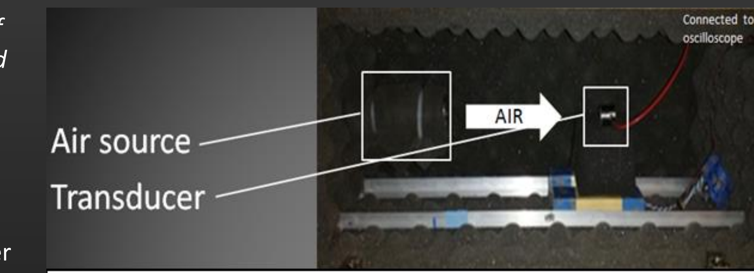


Graph 4: Welch Power Distribution for the transducer. The resonant peak can be seen at 111 kHz

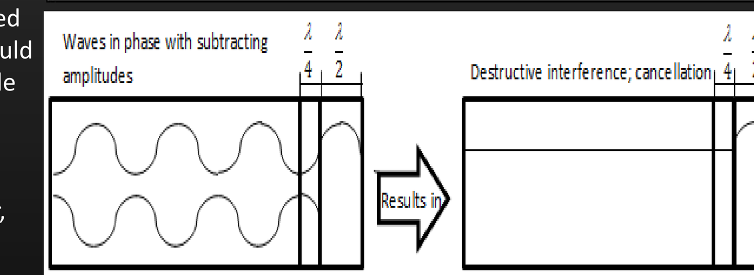


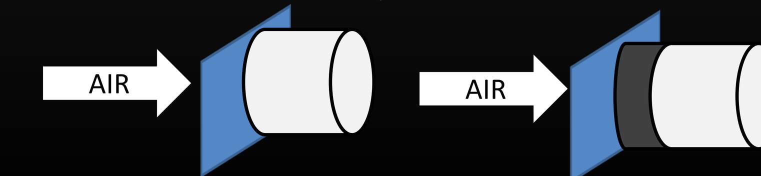
Graph 5: Welch Power Distribution for transducer alone (blue), transducer/glass (green), and transducer/matching layer/glass (red, brown)

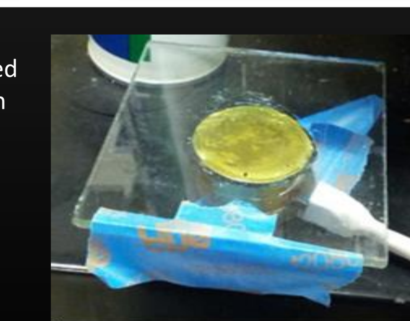
4. A wafer was cut from the sample of correct acoustic impedance and tested to see whether it improved acoustic transducer sensitivity.
A. The resonant frequency of the transducer (which was equal to the bubble sound frequency) was determined by creating a Welch Power Distribution (WPD) graph with the glass layer.
C. The wafer was cut from the sample of correct acoustic impedance and sanded to one fourth the wavelength that would make its frequency equal to the bubble sound frequency (which was equal to the resonant frequency of the transducer). This way, the reflected sound waves would cancel each other, resulting in minimum reflection and maximum propagation to the transducer.
D. The wafer was then placed between a layer of glass and the selected transducer (and coupled with Glacier Grease) and another WPD graph was created.
E. The WPDs were compared to see whether the wafer increased acoustic transducer sensitivity.



This photograph shows the setup used to create a Welch Power Distribution graph for the transducer.







This is a photograph of the transducer with the glass, before the matching layer was inserted.

RESULTS

Using the data from Table 1, the acoustic impedances were plotted against percent tungsten carbide by mass for each sample in Graph 1, and the acoustic impedances were plotted against percent tungsten carbide by volume for each sample in Graph 3. As shown by the black indicator lines on Graph 3, the 51.9% tungsten carbide by volume sample had an acoustic impedance equal to the goal impedance of 13.9 MRayl. For this reason, the matching layer was made from 51.9% tungsten carbide by volume.

Graph 2 shows that the speed of sound propagation through the 13.9 MRayl sample is 1530 m/s, and Graph 4 shows that the resonant frequency of the transducer (which is equal to the frequency of the bubble sounds) is 111 kHz. These values were then used in the matching layer goal thickness calculation (Table 2).

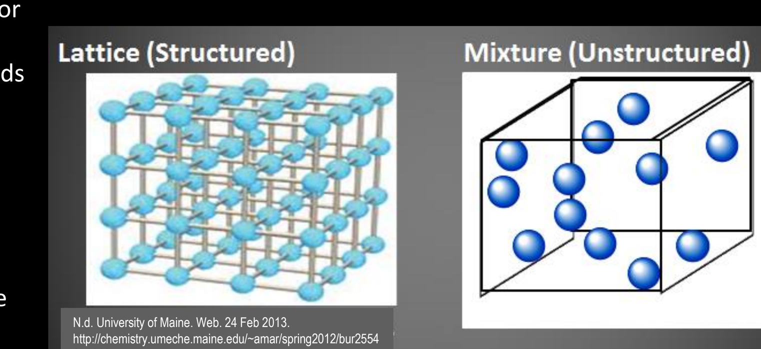
Graph 5 shows superimposed Welch Power Distributions of the transducer alone, with glass, with glass and a small matching layer, and with glass and a large matching layer. The large matching layer was created because the small matching layer's inability to cover the whole sensor could have contributed to the resulting damping effect. However, as seen on the graph, both the small and large matching layers attenuated of the resonant peak of the transducer instead of amplifying it.

DISCUSSION

The results did not support the hypothesis that COUPP's acoustic sensors can be improved with a tungsten carbide powder and epoxy composite matching layer of optimal acoustic impedance and thickness. Although the matching layer was made with the correct acoustic impedance and thickness, it attenuated the sound waves rather than amplifying them. To test whether this result could have been caused by the inability of the matching layer to fully cover the sensor, a larger matching layer was created and tested. Still, however, the matching layer resulted in signal damping rather than signal amplification.

One possible reason that the tungsten carbide powder and epoxy composite attenuated the sound wave is that there may have been tiny air pockets in the composite. Even though dissolved air was removed from the mixture with the bell jar gas evacuation chamber, air may have been reintroduced into the mixture when it was packed into the mold. Air pockets would have created density fluctuations, which would have lead to acoustic impedance fluctuations, resulting in significant reflection and scattering.

Another possible explanation for the composite attenuating the sound wave is that a material needs a structured lattice for sound to propagate effectively through it. However, because the tungsten carbide powder and epoxy composite used in this project consisted of tungsten carbide bits randomly suspended in epoxy, the composite most likely was unstructured rather than crystalline. Lack of structure would result in density fluctuations throughout the composite, which would have lead to acoustic impedance fluctuations and therefore reflection and scattering.



Although the tungsten carbide powder and epoxy composite may not be an ideal matching layer material, it will be used for a backing layer for the acoustic transducers in the COUPP experiment. A backing layer is used to decrease transducer ringing by absorbing sound once it has already traveled to the transducer, thereby improving resolution and frequency range.

CONCLUSION

The hypothesis, that COUPP's acoustic sensors can be improved with a tungsten carbide powder and epoxy composite matching layer of optimal acoustic impedance and thickness, was not supported by the results of this project. Instead of amplifying the sound wave, the composite attenuated the wave. However, because it absorbs sound well, the composite will be used as a backing layer. In the future, a material with a lattice structure may be tested as a matching layer for COUPP's acoustic transducers.

ALL GRAPHS AND PICTURES WERE CREATED BY THE RESEARCHER