Simulating the Temperatures and Pressures of a COUPP Dark Matter Detector

Written by Austin Conner

Edited by Mark Klehfoth and Savanna Annis

Abstract:

It is well known today that there is much more mass in the Universe than can be attributed to atoms or other known particles.[1,2,3] This invisible mass has been dubbed dark matter. While little is currently known about dark matter, there are a few hypotheses about what properties this matter would have to possess. The COUPP experiment is attempting to use superheated-liquid bubble chambers to detect dark matter candidate particles called WIMPs, which are posited to interact with ordinary matter via the weak nuclear force. When a dark matter particle collides with a target nucleus, it causes an observable phase transition from a liquid to a gas. This target liquid is kept at high temperatures inside a quartz jar and experiences frequent pressure fluctuation. To protect the jar from breaking, it is kept submerged within a larger pressure vessel filled with propylene glycol at the same temperatures and pressures. Acoustic sensors analyze sound waves created by the bubbles formed during the phase transition. The pressures, temperatures, and chemistry in the larger pressure vessel create a very harsh environment. This paper describes the design and commissioning of an apparatus to study the short and long-term effects of these harsh conditions on any of the components placed in the compression fluid, such as the acoustic sensors.

* * *

I. Dark Matter and COUPP

Astronomical observations over the past eighty years have indicated that there could be something more to our Universe than we can see. In 1933, Fritz Zwicky discovered an anomaly while determining the mass of the Coma Galaxy Cluster; the mass calculated from kinetic energy due to gravitational forces was much larger than that of the mass predicted by the luminosity, or brightness, of the galaxy.[1] Zwicky postulated that there must be something present in the galaxy cluster that was contributing to the mass but was inherently invisible which he called "Dunkel Materie," or dark matter. Other observations—such as galaxy rotation that conflicts with Newton's Universal Law of Gravitation,[2] gravitational lensing, big bang nucleosynthesis (BBN), and the bottom-up model for structure formation—lead today's scientific community to conclude that 85% of the mass of the Universe is comprised of this mysterious dark matter.[3]

Chicagoland Observatory of Underground Particle Physics (COUPP) is a scientific collaboration using superheated-liquid bubble chambers in an attempt to detect a particular theoretical type of dark matter called Weakly Interacting Massive Particles (WIMPs). WIMPs are classified as "cold" (moving much slower than the speed of light) and posited to interact with other particles through the weak nuclear force, meaning that a WIMP could collide with the nucleus of another particle. This very rare collision, called a weak nuclear interaction, would transfer a small amount of energy from the WIMP to the target nucleus. COUPP's superheated-liquid bubble chambers contain a jar of fluid (CF_3I) which is brought to a superheated state. In this state, the liquid is above its boiling temperature, but is purified and stable enough to remain a liquid. This superheated liquid serves as a target for the WIMP particles. When a WIMP collides with a nucleus of the target fluid, the small amount of energy that is transferred—if deposited in a small enough volume of space—is enough to cause the target fluid to undergo a violent phase transition. The transition from liquid to gas magnifies the atomic interaction between the WIMP and the target nucleus to a scale where it may be observed with the naked eye.

By pressurizing the target fluid, the phase transition due to a collision will produce only a single bubble rather than changing the entire volume into a gas. To avoid strain on the target fluid's containment jar, it is submerged in a larger pressure vessel filled with propylene glycol and kept at the same temperatures and pressures as the target fluid.

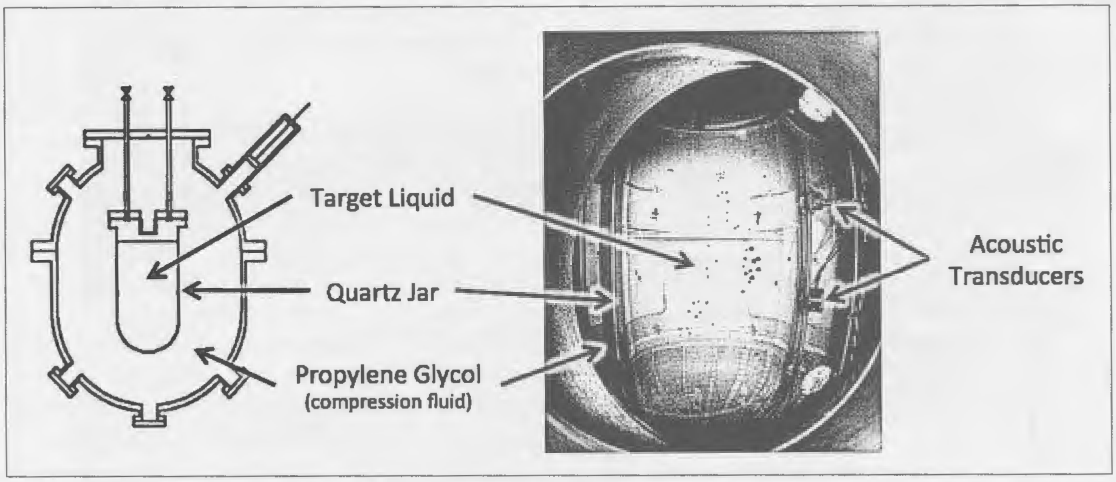

Figure 1. Diagram (left) of COUPP bubble chamber and photo (right) of transducers attached to quartz jar of 60kg detector.

Unfortunately, any particle that deposits energy into the liquid, such as cosmic rays and radioactive decay particles, can also cause events in the COUPP detector. Events from these sources are referred to as background, and they must be identified and reduced as much as possible. The detector is sited two kilometers underground at SNOLAB in Ontario, Canada, to shield the experiment from cosmic rays. By running the detector at a moderate superheat, beta and gamma particles are unable to deposit energy densely enough to cause a bubble to form.

Events due to neutrons can be discriminated from WIMP events using two methods. First, the relatively short mean free path of neutrons can cause them to collide with multiple nuclei and produce multi-bubble events, whereas WIMPs would only cause single-bubble events. By observing the amount of multi-bubble events, it is possible to infer the number of single-bubble events due to neutrons. Second, neutron events would also have an observable spatial dependence, occurring more frequently near the outer edges of the target fluid container and less frequently near the center. WIMP events would have no spatial dependence, occurring uniformly throughout the target fluid.

Background events due to alpha particles (emitted in radioactive decay of contaminants) can be discriminated acoustically with the use of piezoelectric acoustic transducers manufactured at Indiana University South Bend. The transducers are attached to the outside of the quartz jar (Figure 1) containing the target liquid and record the sound produced by every event bubble. It was discovered that the transducers are sensitive enough to discern the difference between bubbles caused by alpha particles and those caused by neutrons.[4,5]

II. Simulating the conditions of COUPP

To avoid a strain on the target fluid's containment jar, it is submerged in a larger pressure vessel which is filled with propylene glycol and kept at the same temperatures and pressures as the target fluid. The corrosive properties of propylene glycol, high temperatures, and pressure cycling create a very harsh environment for any materials and devices, such as acoustic transducers used in the COUPP detectors. In order to understand the possible effects of such an environment, IUSB's team constructed a device to simulate the pressures, temperatures, and chemistry of the COUPP detector's pressure vessel. This device, referred to as the "pressure vessel simulator" (PVS), simulates these conditions inside a test cylinder which is pressurized with propylene glycol and brought to temperature using a simple temperature bath. A diagram of the PVS and its main components is shown in Figure 2.

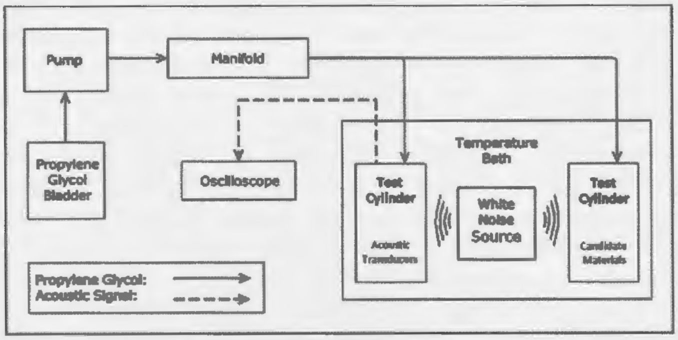

Figure 2. Diagram of Pressure Vessel Simulator: Propylene glycol is pumped through the manifold which regulates the pressure. The propylene glycol is then sent into the test cylinders, pressurizing them in the process. Test cylinders are located in the heated temperature bath. Materials are placed in the test cylinders and observed. For acoustic transducer testing, a white-noise source is built into the wall of the temperature bath. Feedthroughs on the test cylinders allow for power to be sent in to the transducers and acoustic signals to be sent out to the oscilloscope for analysis.

This device allows for testing to determine the longevity of items placed in the COUPP pressure vessel, the acoustic performance and characteristics of the acoustic transducers, and the effects of differing temperatures and pressures on the performance of the transducer. The main concerns when designing the pressure vessel simulator were its functionality, safety, and how well it replicated COUPP's detector. The details of the PVS will be discussed in three parts: the pressure control, test cylinders, and temperature bath. Since COUPP's equipment is made of stainless steel, all components of the test cylinders and manifold were constructed entirely of stainless steel, unless otherwise noted.

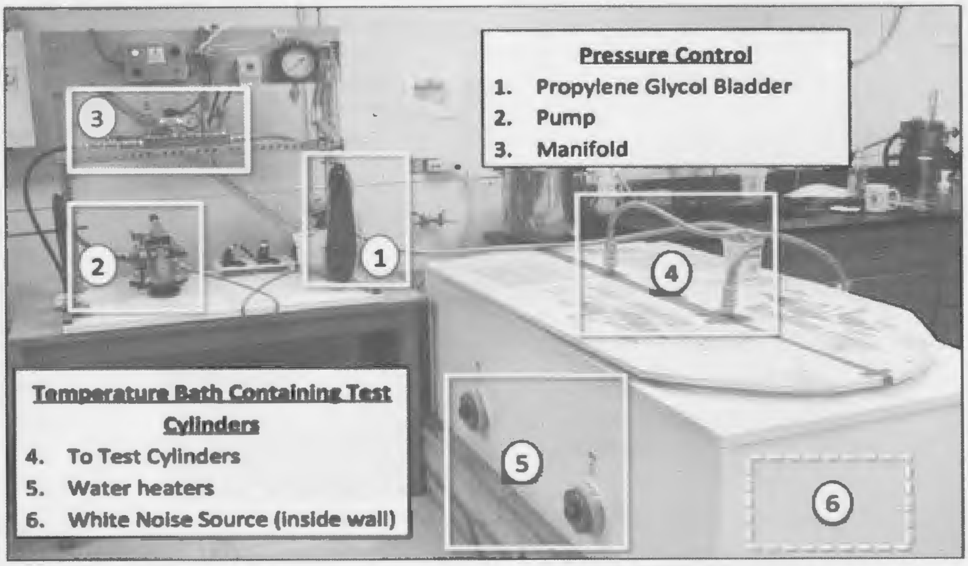

Figure 3. Constructed pressure vessel simulator with components noted.

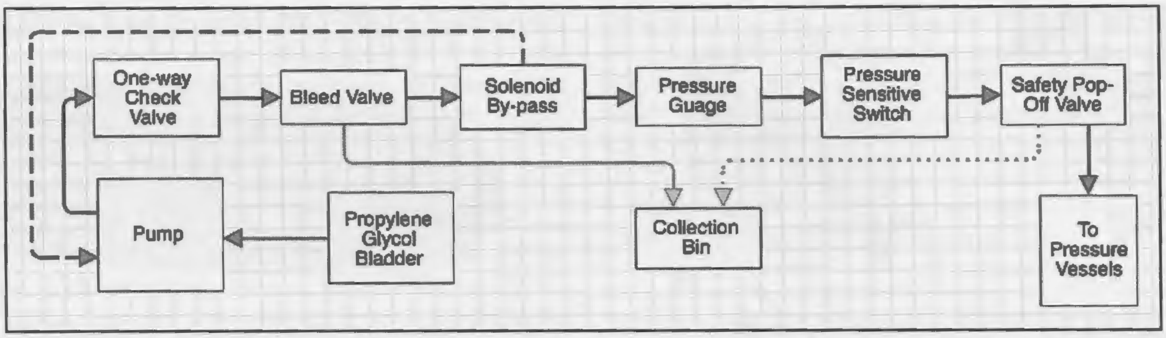

Figure 4. Diagram of manifold components: arrows indicate flow of propylene glycol and represent different modes of operation. Solid black = pressurized; dashed black = depressurized; solid grey = manual release flow; dotted grey = emergency release flow.

A hydrostatic pump generates all pressure for the device. When the system is turned on, the pump pulls the propylene glycol from an airtight bladder, sending it through a one-way check valve and into the manifold (Figure 4). On the manifold is a pressure-sensitive switch which shuts off the pump once the desired pressure has been reached. The one-way check valve keeps the propylene glycol from going back into the pump and sustains pressure. From the manifold, the propylene glycol goes through another hose and into the test cylinders.

A bleed valve on the manifold allows for the manual draining of propylene glycol through a rubber hose and into a collection bin. The bleed valve can also be used to quickly and easily lower the pressure to any desired level for tests involving specific pressure levels.

An electronic timer turns off the pump and opens a solenoid valve for 15 minutes every hour, leaving the system depressurized. The timer closes the valve and turns the pump back on for the remaining 45 minutes. Cycling the pressure in this way and using pressures greater than those used in the COUPP detector accelerates the effects this environment has on the materials being tested. Also located on the manifold is a pop-off valve to drain propylene glycol from the system, as a safety precaution if the pressure rises above 300 psi.

The testing cylinders (in Figure 6) were built to be extremely durable, safe, and versatile. Currently, four cylinders have been constructed, all having a similar design. The propylene glycol enters through a quick connect at the top of the cylinder. Below the quick connect is a cross used for getting electrical wires into the cylinder. Below the cross is a testing area 4" in diameter and 7 to 8 inches deep. Each cylinder was built with a union to allow for easy access to the testing area and sealed with a thick rubber gasket.

To be able to power electrical components inside the test cylinder while at pressure, leak-proof feedthroughs (Figure 7) were designed to allow electrical wires to enter the cylinder through the cross fitting. If a leak in the wire coating were to form inside the cylinder, the pressure would cause propylene glycol to travel through the wire coating, out of the cylinder, and into whatever electronics were connected to the wires. To prevent this, the wires in the feedthrough are stripped of their plastic coating, soldered to pin connectors, and encased in J-B Weld brand epoxy inside a nut which screws into the cross. Having the pin connector in the path of the wire stops the flow of propylene glycol in the event of a leak.

The temperature bath (Figure 8) was built using a galvanized steel trough. In order to ensure the trough was completely leak-proof, the seams are coated with J-B Weld and the entire trough is painted with a coal tar epoxy. The bath is filled with deionized water and a ¼" layer of mineral oil which prevents evaporation of the water. A dividing wall is built in the middle of the trough, dividing the bath into two equal volumes. An electronic water heater is installed in each division, allowing for concurrent testing at different temperatures.

For testing acoustic transducer performance, it is desirable to have an acoustic signal containing a wide range of frequencies at the same acoustic power. Such a signal is referred to as white noise. White noise is generated on the PVS by sending a regulated volume of air through small holes drilled in a brass pipe. This pipe is attached directly to the side of the temperature bath.

Figure 5. Manifold with components noted.

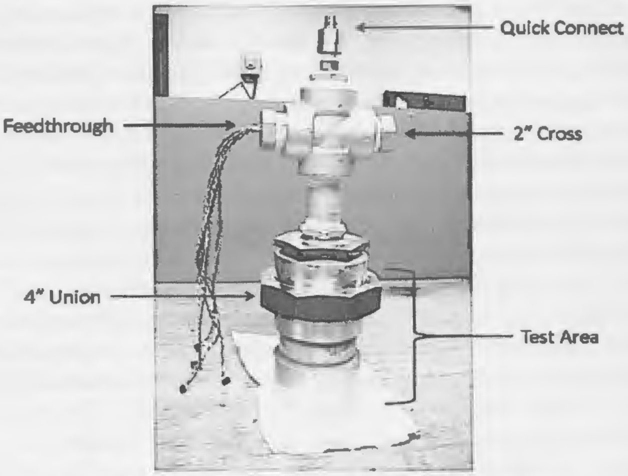

Figure 6. Test cylinder with 2"cross, a feedthrough with protruding wires, and 4" union.

Figure 7. Test Cylinder Feedthrough: (clockwise from upper left) tapered cone drilling of nut and group of 4 pin connectors to be sealed inside the nut; wires soldered to pin connectors and encased in J-B Weld inside the hollow plug; full feedthrough containing 4 sets of wires.

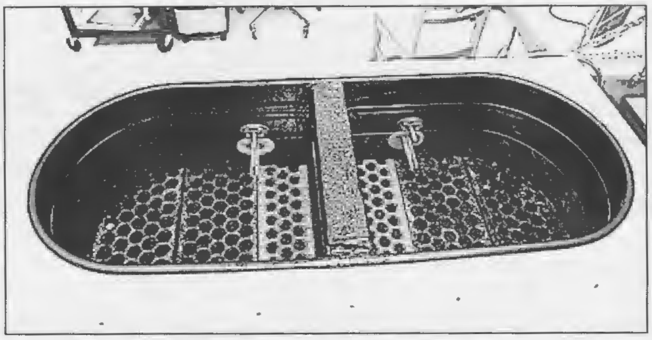

Figure 8. View of divided temperature bath. A heater and leak failsafe can be seen to the left and right of the central division. Bottom of bath is covered with aluminum grates.

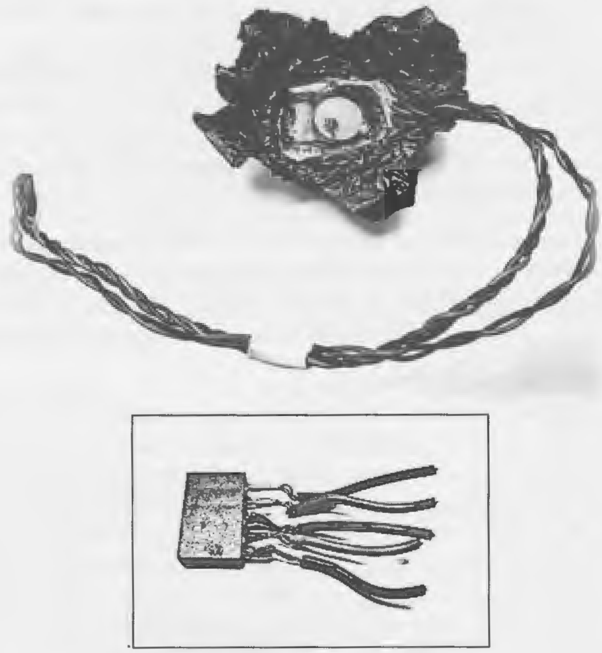

Figure 9. Upper: the 60kg transducer.
Lower: original header connector with visible corrosion.

III. Acoustic Transducer Testing

The great advantage of the pressure vessel simulator is its testing versatility. A number of tests dealing with acoustic transducers and potential materials have already been conducted using the PVS, including live testing of transducer designs confirming functionality of built unit, and understanding acoustic transducer performance as a function of temperature and pressure. In addition, the PVS has been used to explore the durability of two epoxies (Eco-Bond and 3M Scotch-Weld) for their potential use in transducer construction.

Due to the intended long-term use of the acoustic transducers and the difficulty of replacing them on the COUPP detectors, it is desirable to know the approximate life span of a transducer. In May of 2010, a transducer of the same design as one installed on the COUPP 60kg detector was submerged in propylene glycol inside a test cylinder. The device was tested periodically for functionality with no signs of failure until June 2011. On June 13th the voltage-versus-time signal was locked at the positive rail (5 volts) and tapping the transducer produced negative spikes in the signal. Believing the problem to be corrosion of the bare wire at the header connector (Figure 9), the last inch of wire (including original connector) was removed and a new connector was attached. No changes were observed after the attachment of the new connector, so additional wire was removed and the transducer was retested. This process was repeated until the transducer was left with roughly 6 inches of wire. This transducer still produced no usable signal. Further research to determine the cause of the transducer's failure is in progress. The acoustic transducers were inserted into the PVS for testing of any immediate failures before they were installed in the COUPP 4 kg detector. The four transducers were in the PVS for four days, experiencing pressure cycling (96 cycles total) from 0 to 250 psi at 60°C. All transducers functioned after testing and were approved for COUPP. The COUPP detector is operated at varying temperatures and pressures; therefore, it would be advantageous to understand the effect of differing temperatures and pressures on the performance of the acoustic transducers. To test the PVS's ability to record frequency responses at various temperatures and pressures, a number of frequency responses of a transducer were measured at different temperatures (20, 40, and 80°C) and pressures (ranging from 250 to 0 psi) for comparison. The transducer was placed in a test cylinder and connected to an oscilloscope. Once the temperature bath, test cylinder, and its contents were at the desired temperature, the PVS was pressurized to 250 psi. The white noise was turned on, and an analog voltage response from the transducer was recorded using MATLAB. The pressure was then manually lowered in increments of 50 psi using the release valve, and the voltage response recorded at each pressure. This procedure was repeated for all three temperatures.

A fast Fourier transform of the transducer's voltage response was produced using the Welch power distribution in MATLAB. Figure 10 shows the variation in frequency response between the three temperatures, each at 250 and 0 psi. These tests were done using the previously mentioned 60 kg transducer.

Due to the white-noise source being located on the outer wall of the temperature bath, the acoustic signal travels through water and propylene glycol before reaching the acoustic transducer. As the pressure of the PVS fluctuates, so does that of the propylene glycol inside the test cylinder; furthermore, as the temperature of the PVS fluctuates, so does that of the water in the temperature bath and the propylene glycol in the test cylinder. These changes alter the acoustic signal before it reaches the acoustic transducer. In order to achieve a clear understanding of the transducer's dependence on different temperatures and pressures, a new testing method must be developed that removes liquids from the path of the acoustic signal.

IV. Epoxy Testing

As the radioactive background reduction improves in COUPP, even small sources of background radiation become problematic. J-B Weld contains small trace amounts of radioactivity, so it may soon be desirable to use a cleaner epoxy in its place. J-B Weld is used for two purposes: as a transducer backing and an adhesive for attaching transducers to the quartz jar containing COUPP's target liquid. Any replacement epoxy would need to be proven to adhere brass to glass and not degrade under the conditions of the COUPP detector. Eco-Bond and 3M Scotch-Weld (here noted as "3MSW") were tested as two candidate epoxies. Both epoxies were used to adhere small strips of thin brass to slates of glass (Figure 11). Three test samples were created with each epoxy: two for testing and one as a control for comparisons. While the cured 3MSW was clear and without bubbles, the cured Eco-Bond contained many tiny visible bubbles which could cause unwanted effects on acoustic signals. It was, therefore, determined that Eco-Bond should not be used as an epoxy for transducer construction or for adhesion to the quartz jar.

One test sample of 3MSW was placed in a beaker of propylene glycol for two weeks, showing no observable signs of weakening or degradation during this time. For further study, the test sample was placed in a test cylinder and sealed for three months. During the first three weeks of the three-month test, the cylinder was kept at 60 °C and 250 psi. For the remaining nine weeks, it was kept at room temperature and atmospheric pressure. At the completion of the three-month test, there was still no observable difference between the test and the control samples of 3MSW, and neither sample could be pried from the glass slide.

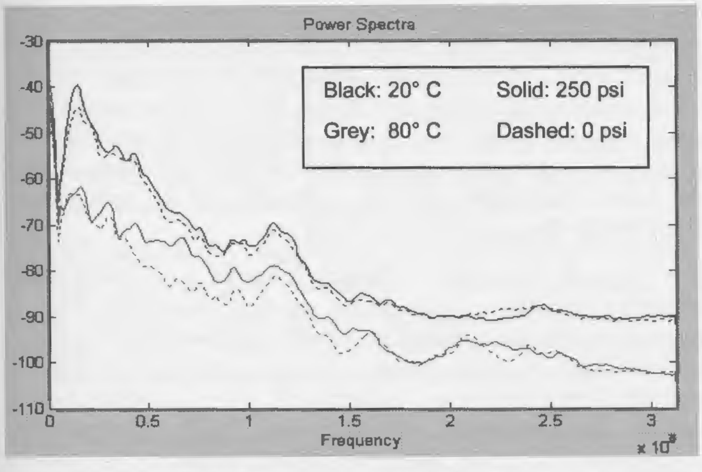

Figure 10. Plot of acoustic power (dB) vs. frequency (Hz). FFT of voltage vs. time response of acoustic transducer at pressure and temperature extremes.

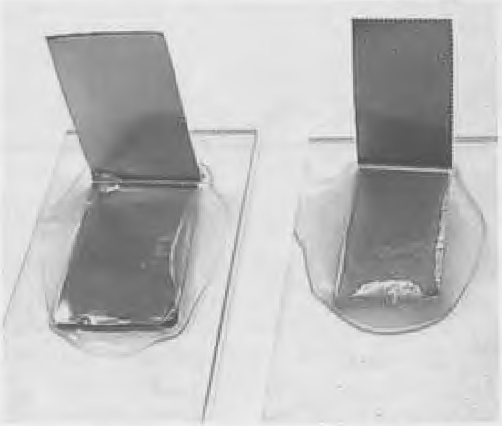

Figure 11. Test samples of 3M Scotch-Weld (left) and Eco-Bond (right) epoxies used to adhere brass to glass. Note the opaqueness of the Eco-Bond due to air bubbles.

V. Summary

The pressure vessel simulator has been built which simulates the temperatures, pressures and chemistry of the COUPP pressure vessel for the purpose of testing the durability and longevity of different materials, such as acoustic transducers and epoxies, before their installation in COUPP. The PVS was used to confirm the functionality of the acoustic transducers that are currently installed on the 4 kg COUPP detector. A transducer replicating the design of those installed on the 60 kg COUPP detector was tested in the PVS from May 2010, until its failure in June 2011, the cause of which is currently being investigated. An initial test was run comparing the response of transducers at varying temperatures and pressures. Modifications are currently in progress here at IUSB to eliminate the liquids as a variable for further testing. Eco-Bond and 3M Scotch-Weld were tested as candidate epoxies for adhering acoustic transducers to COUPP's quartz jar and as a potting material for transducer construction. Eco-Bond was determined through testing to be an unsuitable epoxy. The 3M Scotch-Weld, however, showed no signs of degradation or deterioration after being submerged in propylene glycol both at room temperature and pressure and in the pressure vessel simulator. These initial tests have proven the functionality of the pressure vessel simulator. The reliability of newly developed components, such as low background transducers, can now be tested before implementation on COUPP, providing the collaboration with value insight that can save time and money.

Acknowledgements

Much gratitude goes to Professor Ilan Levine, Edward Behnke, Adam Behnke, Josh Behnke, and William Breznau for their contributions toward the design and construction of the pressure vessel simulator and the analysis of these data results. I would like to thank the National Science Foundation for its support, including grants PHY-0856273, PHY-0555472, and PHY-0919526.

Works Cited

[1] Zwicky, F. (1937). On the masses of nebulae and of clusters of nebulae. *The Astrophysical Journal, 86*, 217-246.

[2] Rubin, V. C., W. K. Ford Jr., and N. Thonnard (1980). Rotational properties of 21 SC galaxies with a large range of luminosities and radii from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc). *The Astrophysical Journal, 86*, 471-487.

[3] Bartelmann, M. (2010). The Dark Universe. *Reviews of Modern Physics, 82*(1), 331–382. doi:10.1103/RevModPhys.82.331

[4] Behnke, E. et al. (2011). Improved Limits on Spin-Dependent WIMP-Proton Interactions from a Two Liter CF_3I Bubble Chamber. *Physical Review Letters*, 106(2), 303-306. doi:10.1103/PhysRevLett.106.021303

[5] Aubin, F. et al. (2008). Discrimination of nuclear recoils from alpha particles with superheated liquids. *New Journal of Physics, 10*. doi:10.1088/1367-2630/10/10/10301