Modifications to, and the use of, a Pressure Vessel Simulator for the COUPP Dark Matter Search Experiment

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Observations of the cosmos have indicated that the majority of the mass in the Universe is in the form of non-luminous matter[1,2]*. This matter does not emit, reflect, or absorb light. Therefore, it has come to be known as 'dark matter'. The COUPP experiment works under the hypothesis that dark matter takes the form of a weakly interacting massive particle. COUPP uses a chamber of superheated liquid as the basis of a dark matter detector. When a dark matter particle interacts with a nucleus in the superheated liquid, via the weak nuclear force, enough energy is transferred to the nucleus to cause a dramatic phase change from liquid to gas. Pressurizing the chamber allows the detector to be returned to a non-superheated liquid state to recover sensitivity for repeated use. The environment inside this detector experiences a wide range of temperatures and pressures which put serious restrictions on what materials and components may be installed in the detector.*

The research presented in this paper describes the effects of such a harsh environment on the acoustic transducers installed in the 4 kg COUPP detector, which has just completed a successful run the SNOLAB deep underground science laboratory (http://www.snolab.ca). These effects were studied by the use of a device capable of replicating this environment called The Pressure Vessel Simulator, (PVS). The design and use of this machine is also described.

The Evidence for Dark Matter

The presence of dark matter is a relatively new concept in our model of the Universe. Dark matter, by its very nature, does not emit or reflect light. This made its detection difficult for optical astronomers. In order to perceive the subtle clues which hint at the existence of dark matter, one needs mathematical models for the forces of nature and optical equipment powerful enough to make measurements of distant galaxies. Throughout most of Human history, these tools were not at our disposal.

It was not until 1937 that the first evidence for dark matter was presented to the scientific community[1]. This evidence came from Fritz Zwicky, who observed the Coma cluster of galaxies and applied a couple mathematical models known at that time to his observations. Zwicky used two different methods for determining the mass of the Coma cluster. One method made use of the Virial Theorem, which provides a general equation relating the average kinetic energy of a system to its average potential energy. From his observations, he was able to model the average kinetic energy of the Coma cluster. The same observations, combined with basic principles of physics, allowed him to also model the potential energy of the Coma cluster. Using these models, and the Virial Theorem, Zwicky was able to calculate a value for the mass of the Coma cluster. The second method Zwicky employed was to

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

[2] V. C. Rubin, W. K. Jr. Ford, N. Thonnard. "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. **238** (June 1980) : 471-487

measure the luminosity of the Coma cluster. Knowing the luminosity, his next step was to use the mass-luminosity relation and obtain a value for the mass of all the stars in the Coma cluster. This, combined with the knowledge of the fraction of atoms in a galaxy that are incorporated into stars, allowed him to calculate a second value for the total mass, in the form of atoms, of the Coma cluster. These two values for the mass were derived independently of one another and since they both applied to the same cluster of galaxies, it was expected that they would be approximately equal to one another. What he found instead was that the mass derived by the Virial Theorem was almost 500 times larger than the mass derived by the mass-luminosity relation[1,3]. This led Fritz Zwicky to assert that there was extra mass in the Coma cluster of galaxies which was interacting gravitationally but not contributing any extra light. He named this extra mass 'dunkel materie,' or 'dark matter.'

Almost 50 years later, in 1980, more observations were made which indicated the presence of dark matter[2]. This time, Vera Rubin and Kent Ford were measuring the rotational speeds of the hydrogen gas around galaxies. This was done by examining the wavelength of the light emitted from a particular region of a galaxy. If the source of the light was moving away from the observer, it would be Doppler-shifted towards a longer wavelength. Likewise, if the source was moving towards the observer, it would be Doppler-shifted towards a shorter wavelength. By examining the magnitude and polarity of this Doppler-shift, one is able to infer the velocity of the light source relative to the observer. In this way, Vera Rubin and Kent Ford calculated the velocity of the gas in the galactic disk at various distances from the core. This allowed them to generate 'rotation curves,' which are plots of the velocity of the gas verses the distance from the galactic core.

Classical physics allows us to predict the velocities of orbiting bodies by equating Newton's law of universal gravitation with an expression for the centripetal force.

$$F_G = G\frac{Mm}{r^2} = \frac{mv^2}{r} = F_C$$

Solving for velocity (v) in the function above, one can generate an expression for orbital velocity as a function of distance (r) from the mass being orbited (M).

$$v(r) = \sqrt{\frac{MG}{r}}$$

If we assume that most of the galaxy's mass resides within the spherical galactic core, and that this core has uniform density (ρ) then we can derive two expressions for the velocity of orbiting material. One expression will describe the velocities of objects within the core, and another will describe objects outside the core. This process reveals that the behavior of orbiting material is very different in these two regions. Within the core, the velocity of orbiting material is linearly proportional to its distance from the center of the galaxy, as shown below.

$$v(r) = r * \sqrt{\tfrac{4}{3}\pi\rho G}$$

Outside the core, of radius R, the velocity of orbiting material is inversely proportional to the square root of its distance from the center of galaxy, as shown below.

$$v(r) = \sqrt{\frac{4\pi\rho G R^3}{3r}}$$

These two equations show that bodies orbiting a galaxy should orbit with velocities which increase with distance inside the core, and decrease with distance outside the core. A plot of this expected behavior is shown in figure 1. However, this sort of behavior is not at all what was observed. Outside of the galactic core, it was discovered that the material in the galactic disk moved with a

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[3] This discrepancy has been reduced to about a factor of 10 by more recent studies.

velocity which either increased with the distance from the core or, for very large galaxies, approached a constant value[2]. The only way to explain this observation of non-decreasing velocity is for there to be much more mass in the galaxy than we can see. This extra, invisible, mass would have to be distributed much more uniformly than the disk of ordinary matter we usually associate with a galaxy.

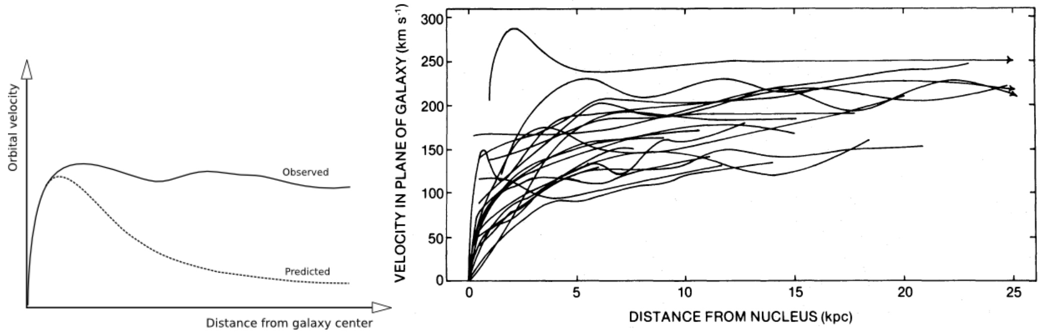

Figure 1 & 2) rotation curves

LEFT: a plot of the predicted velocities shown next to the observed velocities[4].

RIGHT: the actual data collected by Rubin and Ford for 21 spiral galaxies[2].

The evidence for dark matter does not end with the work of these two individuals. The work done by Zwicky, Rubin, and Ford is mentioned here in detail because their work provided the motivation for further inquiry on the subject. Since their discoveries, more evidence for dark matter has been found from sources such as gravitational lensing, the cosmic microwave background radiation, and galaxy cluster collisions. While the evidence for its existence is increasing, no observations made to date provide information regarding the fundamental nature of dark matter. What has been determined is that of all the mass in the Universe, roughly 85% of it is in the form of dark matter[5]. Whatever dark matter is, it must: have mass, move at non-relativistic speeds, and not interact via the electro-magnetic or strong forces.

The Search for Particle Dark Matter

As the evidence for dark matter's existence continues to grow, so too does the race to discover it by direct detection, which searches for evidence of individual nuclei being scattered by individual dark matter particles. However, no one really knows what dark matter is and unfortunately, knowing what to look for is a crucial step in any search. This hurdle is overcome by noting the properties which dark matter must have and comparing those to the properties of various particles implied to exist by posited extensions of the standing laws of physics. Theoretical physicists have been engaged in this practice for decades, and presently there are many competing models which predict the existence of a dark matter particle. An experimental physicist can then pick a compelling model out of the list and devise an experiment which is sensitive to that particular type of dark matter particle. This is how one may conduct a search without knowing exactly what to look for.

A favored solution to the dark matter problem is a class of models suggesting that all dark matter particles are something called "WIMPs". This is an acronym, which stands for: "Weakly Interacting, Massive Particle". A WIMP is a hypothetical particle, imagined to have all the properties that a dark matter particle would need to have. No individual particle or any combination of particles from

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[4] http://en.citizendium.org/wiki/galaxy_rotation_curve

[5] E. Komatsu *et al*. "Five-Year Wilkinson Microwave Anisotropy Probe Observations: Cosmological Interpretation," Astrophysical Journal Supplement Series. **180** (February 2009) : 330-376

the Standard Model[6] of elementary particles would yield all of the characteristics of a WIMP. Therefore, if a WIMP existed, it would have to be an addition to the standard model. The WIMP model also asserts that these particles would be uniformly distributed in a spherical shape around each galaxy. This would explain the rotation curves of galaxies observed by Rubin & Ford, and make it possible to detect these particles without having to leave the comfort of Earth. WIMPs would interact weakly with atoms, just like neutrinos, but they would be much more massive and consequently, they would move much slower than neutrinos. The mass that these particles would have is what would allow them to exert a gravitational influence on celestial bodies. The slow speed of a WIMP simply means it would be non-relativistic in nature, which would allow WIMPs to clump together and form galaxies. As the name would suggest, a WIMP may be quite capable of interacting via the weak force. While this last quality is not required of a dark matter particle in general, it is the only way such a particle would be detectable by direct dark matter search experiments.

COUPP: the Chicagoland Observatory for Underground Particle Physics

COUPP[7] is a collaboration of researchers from the Fermi National Accelerator Laboratory, (Fermilab[8]); the Sudbury Neutrino Observatory Laboratory, (SNOLAB[9]); the University of Chicago[10]; Indiana University South Bend, (IUSB[11]); Virginia Tech[12]; and the Universitat Politècnica de València[13]. This collaboration engages in an ongoing search for WIMP dark matter[14]. Since the WIMP model supposes that dark matter can only interact via the gravitational force or the weak force, these are the only two mechanisms which can be exploited for the purposes of detection. However, the gravitational forces from individual WIMPs are so small that their gravitational influence can only be perceived in aggregate. This means that only the interactions from the weak force could serve as a viable means for directly detecting WIMPS. Assuming a WIMP interacts weakly with some material in a detector, it would only release very small amounts of energy, somewhere between 1-100 keV. Any detector hoping to make use of this interaction would have to employ some method of amplifying this tiny amount of energy.

The COUPP detectors do this by holding a target liquid at a moderate super-heat within a quartz containment vessel. Super-heated liquid is liquid which has been heated beyond its boiling point. It remains a liquid at this temperature because the phase transformation from liquid to gas will not happen without some sort of catalyst. For most boiling experiences in daily life, this catalyst comes in the form of either some impurity in the liquid, or an already present microscopic bubble, clinging to the side of the container. In the COUPP detector, great care is taken to ensure that no such catalyst exists in the target liquid. Because of this, the detector remains in a super-heated liquid state, indefinitely waiting for a WIMP to enter the detector. When a WIMP finds its way into the COUPP detector, there is a small chance that the WIMP could interact weakly with a nucleus of the target liquid. A nucleus recoiling from this collision can deposit sufficient energy in a small enough volume to trigger the phase

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[6] G. Bertone, D. Hooper, J. Silk. "Particle Dark Matter: Evidence, Candidates and Constraints," Physics Reports. **405**,5-6 (January 2005) : 279 - 390

[7] http://www-coupp.fnal.gov

[8] http://www.fnal.gov

[9] http://www.snolab.ca

[10] http://www.uchicago.edu

[11] http://www.iusb.edu

[12] http://www.vt.edu

[13] http://www.upv.es

[14] E. Behnke, *et al.* "Improved Limits on Spin-Dependent WIMP-Proton Interactions from a Two Liter CF_3I Bubble Chamber," Physical Review Letters. **106**,021303 (January 2011) : 1-4

transformation. When this phase transformation occurs, all of the super-heated liquid can violently turn to gas in a brief instant. This 'bubble chamber' technique was invented by Donald Glaser in 1952[15] and is a very clever way to turn an unimaginably tiny interaction into a very observable macroscopic interaction.

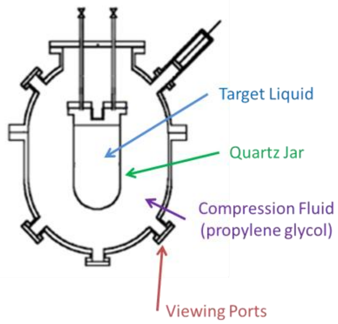

Figure 3) cartoon of the COUPP detector[7]
superheated target liquid in the center, surrounded by propylene glycol held at the same temperatures and pressures as the target liquid. Cameras look through viewing ports and acoustic transducers are attached to quartz jar

During normal operation of the COUPP detector, the super-heated target liquid is not allowed to completely transform into a gas. This is because the detector takes longer to reset with more gas created within the detector. To prevent a full boil, high speed cameras register the change in light created by a macroscopic bubble forming within the chamber. The cameras then trigger a hydraulic system and the container holding the liquid is pressurized. This pressurization collapses the bubble and the fluid is returned to a non-super-heated liquid state. In order to maintain the integrity of the quartz containment vessel during repeated pressurizations, the pressure inside and outside the quartz vessel is always held equal. This is achieved by submerging the entire quartz containment vessel within another, larger, pressure vessel containing propylene glycol. Anytime the target liquid is pressurized, so too is the propylene glycol. This extra step ensures that the walls of the quartz vessel experience no net pressure difference. The propylene glycol environment surrounding the detector also provides a way to uniformly heat the target liquid.

A detector built in this manner provides a reliable method for macroscopic detection of microscopic particle interactions. Unfortunately, there are many particles which are capable of triggering an event in such a detector. An ideal detector would not be triggered by anything other than a WIMP. However, any particle which can interact via the weak force is capable of causing a bubble in the superheated liquid. This includes the wide array of particles raining down in the form of cosmic rays, and the particles involved in radioactive decay processes, such as alphas, betas, gammas, and neutrons. These nuisances to the detection of WIMPs are referred to as 'background' and should be reduced as much as possible to have any confidence in WIMP detection. Ideally, one must also be able to identify each of the background events so that they can be removed from the pool of possible WIMP interactions. COUPP has methodology in place to mitigate or identify each type of background event. COUPP installed their detector 2 km underground, in an active mine near Ontario, Canada[9]. The 2 km thick shield above the detector suppresses cosmic ray background severely. However, being underground tends to increase the background radiation present in the environment. Therefore, the decay products of radioactive processes become a primary concern. If the target liquid is only moderately super-heated, then gamma and beta particles are unable to deposit the energy density required to form a bubble.

Reducing the number of events caused by neutrons and alphas is more challenging. In addition to trying to remove their effect completely, COUPP goes to great lengths to distinguish between events

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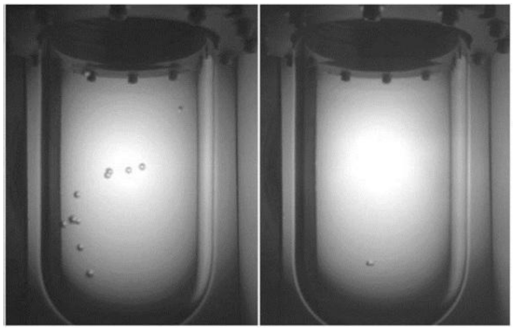
[15] Donald Glaser. "Some effects of ionizing radiation on the formation of bubbles in liquids," Physical Review. **87** (1952) : 665-665

caused by neutrons, alpha particles, and WIMPs. Every bubble event in the detector is recorded on video cameras. Visually examining the bubble formation from the set of data provides a method for discerning the difference between events triggered by neutrons from those caused by WIMPs. Neutrons are far more likely than a WIMP to interact with the target liquid. The mean free path of a neutron in CF_3I is about 5 cm, so neutrons often interact more than once in the detector and create multiple bubbles in a single event. A WIMP so rarely interacts with nuclei that a WIMP will create at most a single bubble. Therefore, by studying the rates of bubble events with multiple bubbles, one can infer the number of single bubble events due to a background neutron flux. The majority of neutron events will form bubbles near the edges of the vessel, whereas bubbles formed from WIMPs do not display this spatial dependence. Therefore, neutron's and WIMP's fluxes can be differentiated statistically from the spatial distribution of events as well. Differentiating between alpha particle events and neutron events is done, not by looking at the bubbles, but by listening to them. Attached to the outer wall of the quartz containment vessel, submerged in propylene glycol, exist multiple piezo-electric, acoustic transducers. A bubble event in the target liquid produces a faint sound wave which travels towards the walls of the quartz vessel. This sound wave is transmitted through the quartz material and enters the acoustic transducer. These transducers record the sounds produced within the containment vessel for each event. Based on the magnitude and the frequency of the sound recorded from a bubble, it is possible to observe characteristic differences between the events triggered by alpha particles and those triggered by neutrons[14,16,17].



Figures 4 & 5) bubble formation in detector[7]

LEFT: A photo of a neutron induced event with multiple bubbles

RIGHT: A photo of a single bubble event, which could indicate a WIMP scattering in the detector

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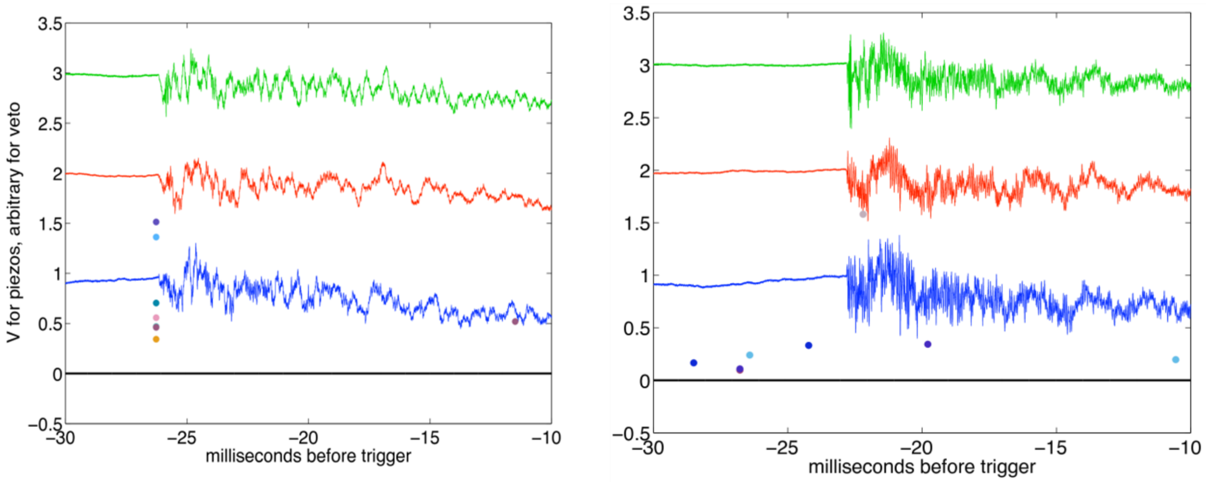
[16] F. Aubin, *et al*. "Discrimination of nuclear recoils from alpha particles with superheated liquids," New Journal of Physics. **10**,103017 (October 2008) : 1-11

[17] The discovery that different subatomic particles make different sounds when traversing matter was made by another experiment that IUSB participates in using acoustic sensors designed and manufactured by IUSB.



Figures 6 & 7) acoustic waveforms from events in super-heated liquid
LEFT: an event triggered by a neutron
RIGHT: an event triggered by an alpha particle

Pressure Vessel Simulator

When acoustic transducers are installed on the COUPP detector, there are limited options as to where they can physically be placed. This is because the purity of the target liquid must be maintained at all times. Introducing foreign objects into the target liquid presents multiple hazards. The microscopic geometry of such an object may present new and undesired sites for bubble nucleation. Also, if the foreign object is in any way radioactive, then the decay products will trigger events which are clearly not WIMP related. This leaves only two options for installation: either within the secondary pressure vessel or on the exterior of the whole apparatus. For acoustic transducers, the desired option is within the secondary pressure vessel, submerged in the propylene glycol environment. This is because the exterior of the detector is too far removed from the target liquid. For instance, an acoustic transducer affixed to the exterior of the detector would measure a sound that originated in the target liquid, travelled through the quartz vessel, through the propylene glycol, and through the steel outer vessel before it finally reached the transducer. At each interface, only approximately 10% of the sound wave is transmitted to the next medium. Therefore, all acoustic transducers are installed on the quartz vessel, within the outer vessel, and constantly exposed to propylene glycol.

The propylene glycol within the outer vessel is subjected to the same temperatures and pressures that the target liquid experiences. This means that anything which gets installed into this environment must be able to withstand the repeated fluctuations in temperature and pressure. Additionally, the materials in this outer vessel should not react with propylene glycol. Propylene glycol is generally non-reactive with most materials. However, some materials, like copper, corrode when exposed to the propylene glycol. For these reasons, it is necessary to examine how materials and components will react to exposure to propylene glycol which is heated and frequently pressurized.

A sample of the material, or the entire component, to be tested is placed within a pressure vessel. The vessel is filled with propylene glycol and sealed. The filled vessel is submerged in water and attached to an apparatus referred to as the "Pressure Vessel Simulator", or PVS, which simulates the outer vessel environment of the COUPP detector[18]. Once activated, the PVS will pump glycol from the bladder into the manifold. The manifold is the interface for all of the sensors, controls, and safety

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[18] Austin Connor. "Simulating the temperatures and pressures of a COUPP dark matter detector," I U South Bend Undergraduate Research Journal. 2012 (May 2012) : 57-62

equipment. The glycol then travels from the manifold to the pressure vessel, which pressurizes the glycol within the vessel. The pressurized glycol is then heated uniformly and held at an elevated temperature by the water in which the vessel is submerged. The PVS keeps the vessel pressurized for a fixed time interval; it then depressurizes the vessel for another fixed time interval. During the depressurization of the vessel, the extra glycol is recycled back into the bladder. To accelerate any adverse effects which might arise from being in the COUPP detector, the PVS cycles between pressure extremes at a higher frequency and operates at temperatures and pressures slightly higher than those used by COUPP. In the PVS, the temperature of the glycol is held at 70°C and the vessel completes a full pressure cycle, between 0 psig and 250 psig, in 8 seconds.

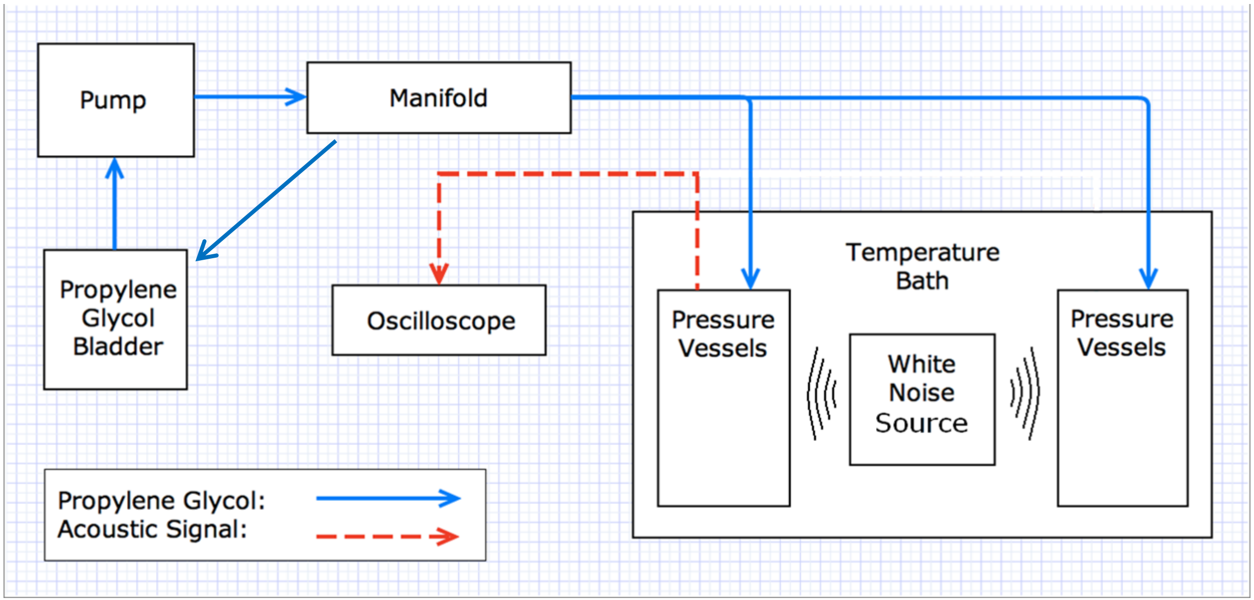


Figure 8) flow chart of the Pressure Vessel Simulator[17]

Much work has been done recently to make the PVS fully automated. Since its construction, reported in [17], several new features have been added which allow for more pressure cycles in a given time interval and grant more control over the duration of each pressure cycle. The first modification to the system, and the most important, was replacing the old hydrostatic pump with a rotary vane pump. The old pump was loud, which meant that the PVS could only be operated for short time intervals, or on nights and weekends. The installment of the rotary vane pump made the PVS nearly silent. This in turn allowed for vessels to be pressure cycled all day, every day. The cycle rate was increased further by installing a new cycle timer which easily allows one to dial in the length of time a vessel would be held at 250 psig and, just as easily, dial in the length of time a vessel would be at 0 psig. This cycle timer improved the cycle rate from one pressure cycle per hour to 450 pressure cycles per hour. This increase in the cycle rate, combined with the quieter pump, greatly increased the number of pressure cycles completed in one day. The old pump and timer combination allowed only 24 pressure cycles in one day. By simply replacing the pump and the timer, this value was increased to over 10,000 pressure cycles achievable in one day. These improvements made it difficult for a human to reliably keep track of the number of pressure cycles completed on one vessel. To accomplish this, a digital counter was installed on the PVS. This unit simply increments a scalar counter after each complete pressure cycle. The final addition to the PVS, which allows for full automation, was the installment of a 7 day timer. The function of this unit is to allow one to program when the PVS should turn on and when it should turn off. With all of these new additions, one only needs to dial in, on the cycle timer, how long one wants a pressure cycle to last and then program the desired operation schedule for a week, on the 7 day timer. After completing these two steps, no further human interaction is required. The PVS will turn itself on and off at the appropriate times and while the PVS is on, it will pressure cycle any vessels attached to it and keep track of the number of complete pressure cycles.

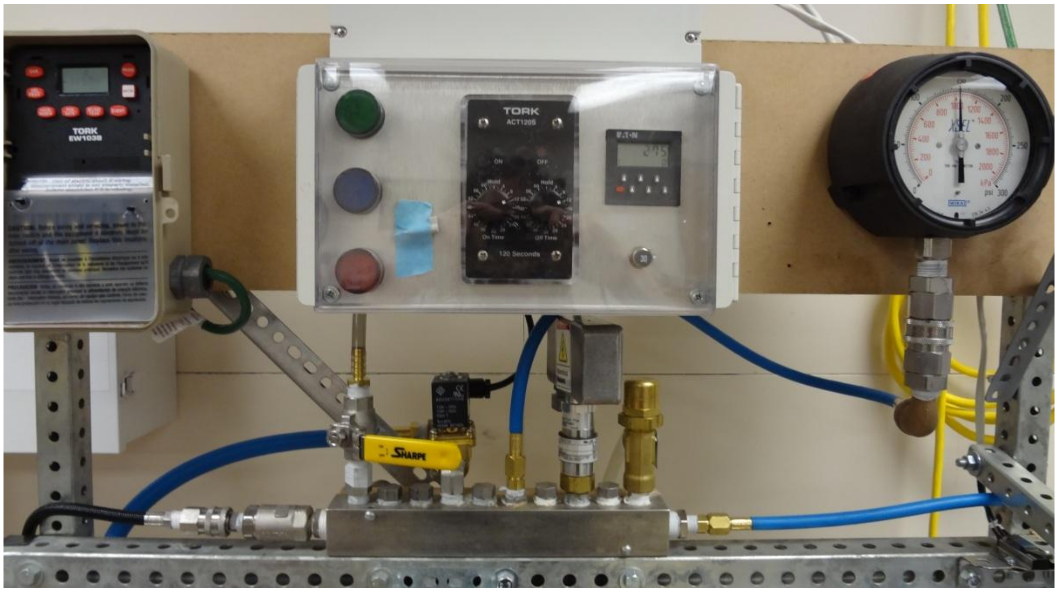


Figure 9) Pressure Vessel Simulator control interface
LEFT: 7 day timer CENTER: indicator lights, cycle timer, and digital counter RIGHT: pressure gauge
BOTTOM CENTER: manifold with yellow bleed valve and various sensors

The PVS is also designed to cycle pressures in multiple vessels simultaneously. Currently, there are 5 fully functional pressure vessels and a temperature bath large enough to accommodate all 5. The pressure vessels attached to the PVS are built entirely out of stainless steel. This is because the outer vessel of the COUPP detector is stainless steel and the primary goal of this apparatus is to simulate the environment of COUPP's outer vessel. Each vessel consists of two main halves, connected by a union. To access the interior of the pressure vessel, one needs only to unscrew the union and separate the two halves. Some pressure vessels are also equipped with an electrical feed-through for testing electronic components, such as acoustic transducers, in-situ. The feed-through allows electrical power to be delivered to the device inside the vessel and allows electrical signal to travel outside of the vessel, even while the vessel is held under pressure. This feature of the pressure vessel allows for testing of electrical components throughout the course of their pressure cycling. The PVS is capable of testing material samples, and to test the performance and lifespan of the acoustic transducers used on the COUPP detector.

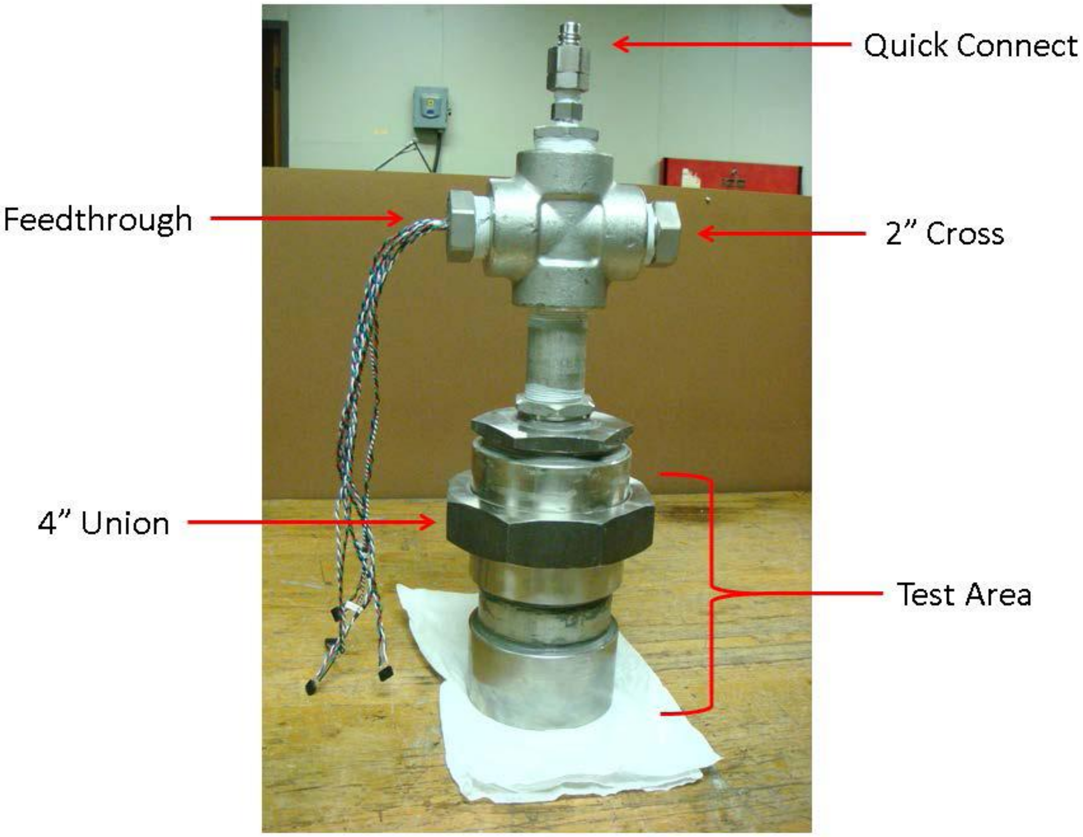


Figure 10) stainless steel pressure vessel[15]

Acoustic Transducer Testing

The acoustic transducers which are attached to the COUPP detector play a vital role in discriminating against background events. When a COUPP detector is underground and actively searching for dark matter, the transducers are expected to survive exposure to heat, pressure, and liquid for long time intervals. There are many concerns regarding the performance of the transducers in this environment. Since it is a rather daunting task to set up a sensitive experiment deep underground, it is helpful to have complete confidence in all sensors installed on the detector. Historically, some transducers have ceased to function during the course of the experiment, therefore every COUPP detector has multiple acoustic transducers installed. There are many things which could go wrong during the experiment and if one or two transducers fail, there are others present to continue to collect data. In an effort to build better and better transducers, new designs are regularly developed, each improving on the last. It is hoped that this iterative process will lead to no, or fewer, failures in future COUPP detectors. It is important to understand both the sensitivity and longevity of each distinct transducer design.

One of the most likely points of failure for the acoustic transducers is the ingress of propylene glycol to the pre-amplifier circuit board. Improving on the design of the encapsulation package for the pre-amplifier might increase the lifetime of the acoustic transducers used in the COUPP experiment. Using low radioactivity materials improves the sensitivity of the COUPP detector. This led to the use of pre-amplifiers printed on a substrate which has never been used in the COUPP detector before. The new, low radioactivity, material is called 'CuFlon'. This is a copper plated fluorocarbon resin, made by the Polyflon Corporation. Three acoustic transducers were constructed in a similar manner as the transducers used in the test NuMI run of the COUPP detector, except that each of them was installed with the new CuFlon pre-amplifiers. Also, these three transducers did not have a full Faraday cage; the lid was left off of each transducer to be able to look for any degradation to the pre-amplifiers after many pressure cycles. Each of these three transducers with CuFlon pre-amplifiers was assigned an arbitrary unit number from 19 - 21. This provided the opportunity to see how these new components might influence the quality of the acoustic transducers under heat and pressure. To ensure the sound input to the transducers is a constant value, all three transducers were epoxied to the interior surface of a pressure vessel. Also, a sound source was permanently affixed to the outer surface of the pressure vessel. The method of attaching the transducers to the vessel, and the method of connecting the wires to the feed-through were the same methods used on the COUPP detector. The pressure vessel was then filled with propylene glycol, sealed, and attached to the PVS.

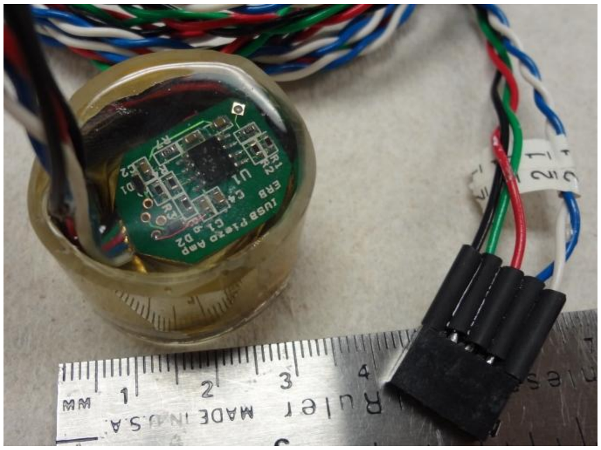
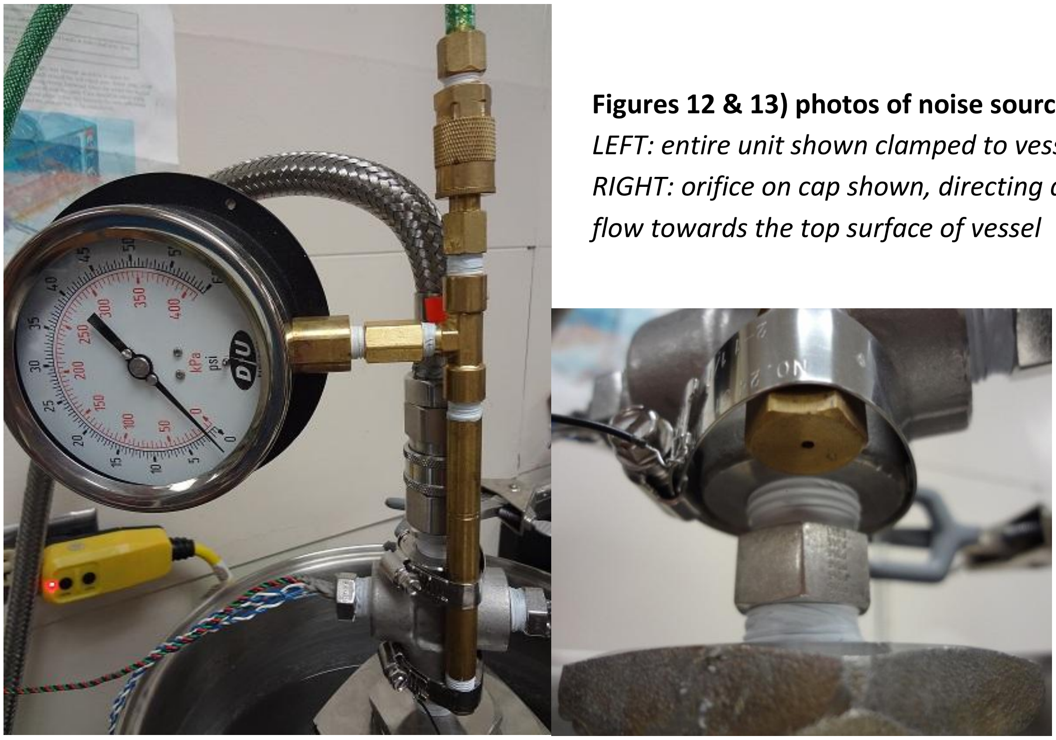


Figure 11) acoustic transducer
Unit 21, one of the 3 transducers made with a CuFlon pre-amplifier and no lid.

Pressure cycling for these transducers began on 08/13/2011 with an 8 second pressure cycle. This means that the vessel was pressurized to 250 pounds per square inch (gauge) for 4 seconds and then depressurized to 0 pounds per square inch (gauge) for another 4 seconds. Once a week, the PVS would be turned off, and the vessel depressurized. Then, the vessel would be exposed to a noise source.

The noise source was fabricated by feeding compressed air into a 6 inch long brass pipe and out a single orifice in a cap on the brass pipe. The orifice in the cap is 5/64 of an inch in diameter. This noise source is placed 1 inch away from the top surface of the pressure vessel and secured in place with ring clamps. The noise source is oriented so that the air forced out of the orifice is directed towards the top surface of the pressure vessel. The air pressure in the brass pipe is maintained at 20 pounds per square inch (gauge) to ensure uniformity in the sound between measurements. This noise source was not efficient at producing high frequency noise. An ideal white noise source would produce noise at around the same intensity for all frequencies.



Figures 12 & 13) photos of noise source
LEFT: entire unit shown clamped to vessel
RIGHT: orifice on cap shown, directing air flow towards the top surface of vessel

During this exposure to noise, the individual transducers were connected, via wires in the feed-through, directly to an oscilloscope. The oscilloscope used in this study was the "DPO2024" model produced by Tektronix, Inc.[19]. The oscilloscope was connected to a computer running MATLAB software[20]. In MATLAB, the raw signal from the transducer was converted into a power spectrum. This sort of signal processing clearly indicates how well the transducers measure the different frequencies of sound. This procedure of exposing a depressurized vessel to noise and creating a spectrum for each transducer was carried out in the same fashion each week. In between measurements, the PVS automatically pressure cycled the vessel. Each collected spectrum was labeled with the appropriate unit number and the number of completed pressure cycles. The spectra taken at different numbers of pressure cycles for each individual transducer are then superimposed on top of one another. This allows one to see the performance of each transducer over time. The spectra constructed over the length of the test are portrayed on the next page.

Lifetime Data

Each power spectrum in this section represents the data collected over time for an individual acoustic transducer. The associated unit number is noted below each plot and the number of pressure cycles which the transducer has experienced is represented by the displayed color scheme. For all spectra, the vertical axis is acoustic intensity, expressed in decibels, and the horizontal axis is the sound frequency, in Hertz.

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[19] http://www.tek.com
[20] http://www.mathworks.com/products/matlab

🟪	40,000 pressure cycles
⬛	50,000 pressure cycles
🟦	60,000 pressure cycles
🟩	65,000 pressure cycles
🟥	68,000 pressure cycles
🟦	74,000 pressure cycles
🟨	166,000 pressure cycles

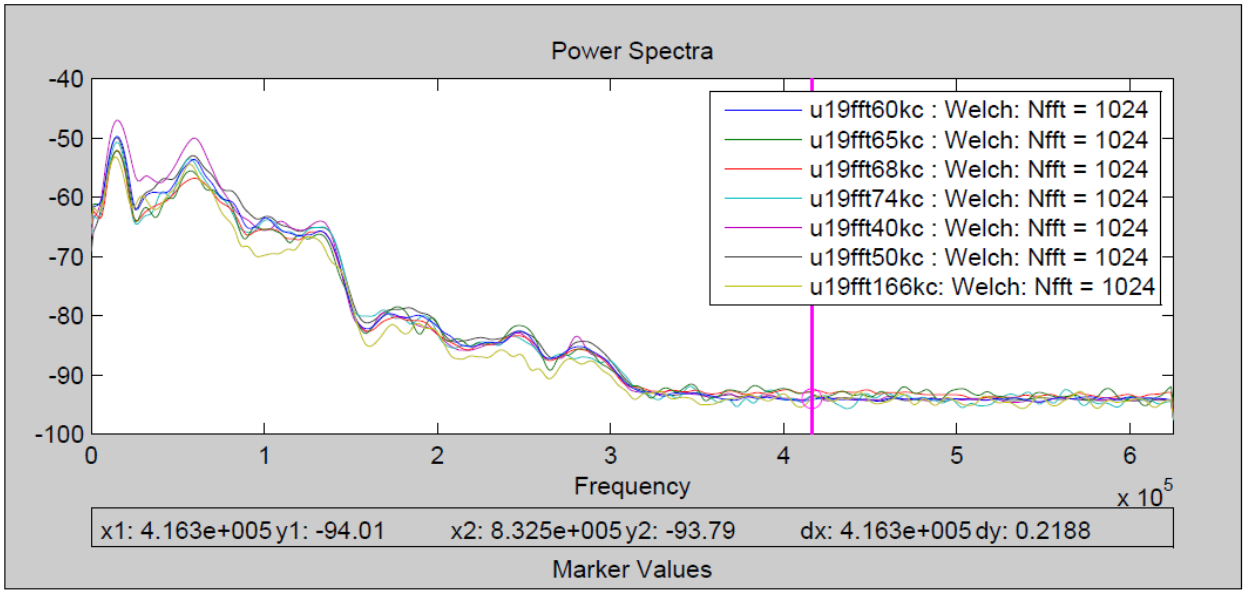

Figure 14) power spectra for unit 19

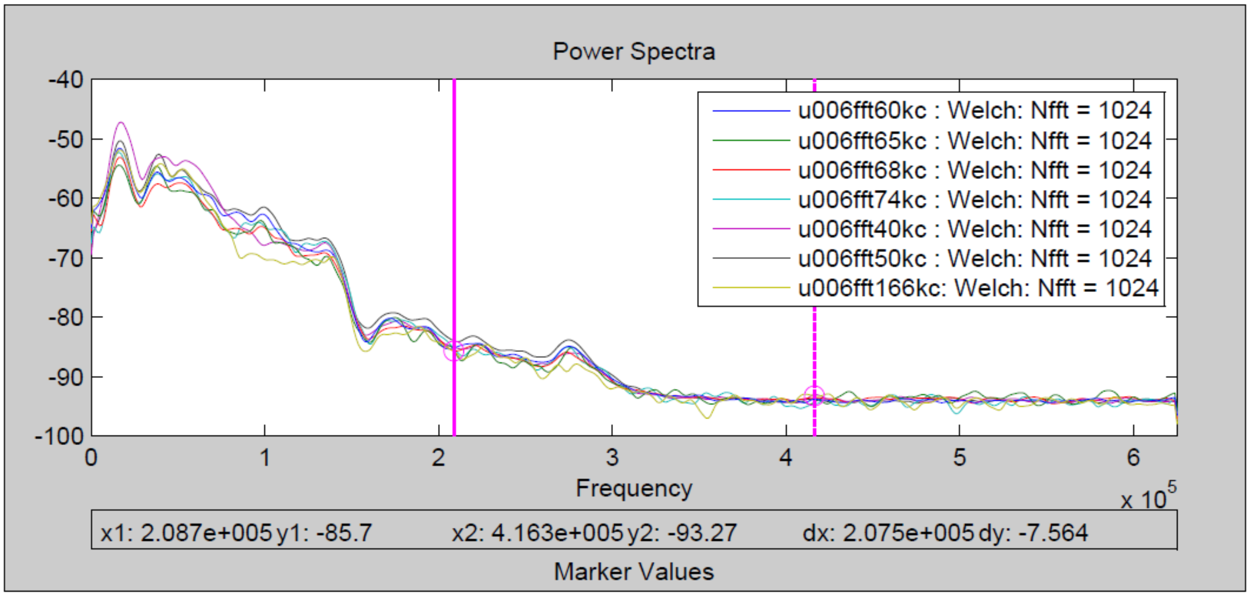

Figure 15) power spectra for unit 20

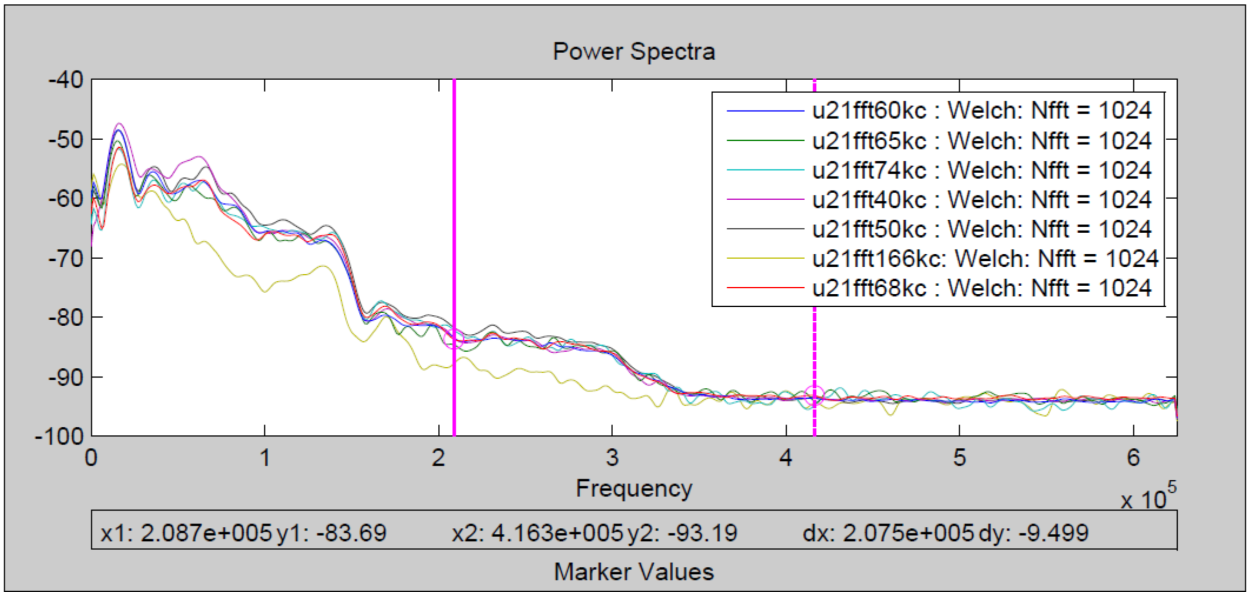

Figure 16) power spectra for unit 21

Initial and final comparisons

Pressure cycling began on 08/03/2011 and was stopped on 01/06/2012 for a total of approximately 166,000 pressure cycles. A problem with the PVS system was noticed on 01/06/12 and pressure cycling was halted. After a complete rewiring and some motor maintenance, pressure cycling resumed between 03/23/12 and 06/28/12. During this time approx. 12,000 pressure cycles occurred. No tests were performed on the transducers between 01/06/12 (166,000 cycles) and 06/28/12 (178,000 cycles). The tests taken on 06/28/12 indicated that there was a problem with the transducers. It should be noted that due to intermittent tests, any failures which occurred could have occurred by 166,000 pressure cycles. The vessel was opened on 07/06/12 to examine the quality of the transducers.

It was expected that the J-B Weld epoxy used to secure the transducers to the pressure vessel would outlast the lifetime of the transducers themselves. However, upon opening the pressure vessel, it became immediately apparent that all of the transducers were either very loosely attached, or not attached at all, to the bottom surface of the vessel. It is unknown at what point the J-B Weld bond failed between the brass of the transducer and the stainless steel of the vessel. It should be noted however that this is not an issue which would affect COUPP's detectors. This is because in the detector, the J-B Weld bond is between the brass of the transducer and the quartz of the inner vessel. At no point in the detector is a component adhered to stainless steel by the use of J-B Weld.

In an attempt to replicate COUPP's method of transducer attachment, all of the transducers were electrically connected by a simple solder joint, which was covered by adhesive lined shrink tubing. The wire then led to a mock feed-through which isolates the solder joint. In order for the top and bottom of the pressure vessel to be completely removed from one another, header connections were installed in the wire. Female header connectors were used on the lower half of the pressure vessel and male header connectors were used in the top half. This wire arrangement leading from the transducer to the pressure vessel feed-through can be seen in figure 17.

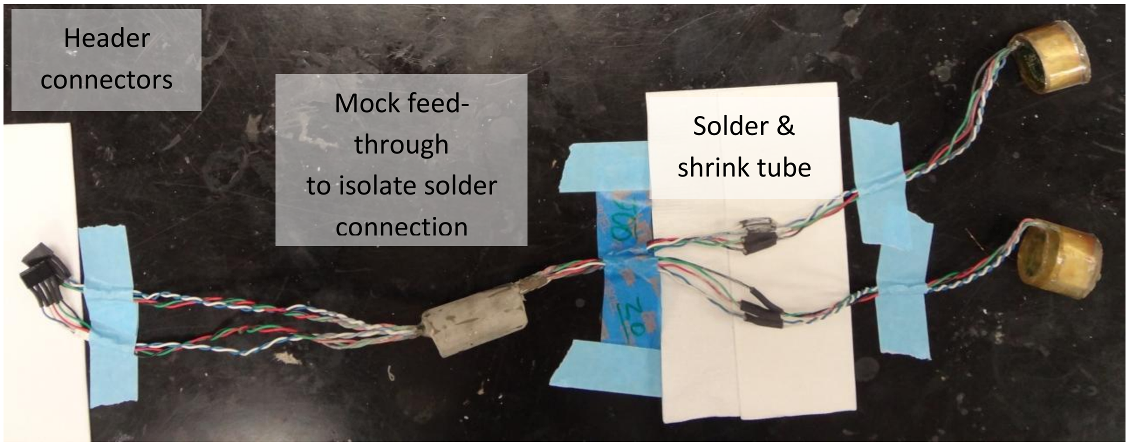

Figure 17) Feed-through assembly

This photo depicts the various elements connected to the feed-through wire inside the pressure vessel.

Propylene glycol could make its way into the transducers through an opening in the solder joint, making this connection a possible point of failure. To ensure that the solder joint was still a reliable connection, each transducer was hooked to an oscilloscope via the header connectors shown on the left hand side of figure 17. When this procedure was carried out, normal transducer response was seen on the oscilloscope, indicating no faults in the assembly shown in figure 17.

Male header connectors were installed in the top half of the feed-through, within the pressure vessel. These consisted of exposed metal pins. Upon opening the vessel it was apparent that some material, blackish in hue, had built up on these pins. The material was concentrated on the red (+5V) pins and the black (ground) pins. The photo below shows this material as it looked shortly after opening the vessel. It should be noted that this material build up could be a product of the PVS system used at IU South Bend, and not present in the COUPP detectors. This is because the pump installed on the PVS uses graphite as a lubricant and the vessel attached to the PVS uses rubberized cork as a gasket material. Both of these materials could contribute to the dark colored material seen on the header connectors and neither material is present in COUPP's detector.

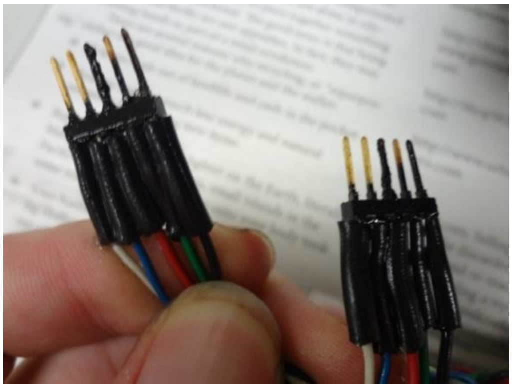

Figure 18) Build up on connector pins

This photo shows the male header connectors with unknown material on the pins.

As mentioned before in this document, these transducers were among the first to be constructed with CuFlon pre-amplifier circuit boards. To visually check the integrity of these boards, each transducer installed in the pressure vessel was constructed without a full faraday cage. This construction technique, combined with the use of a clear epoxy, allows one to see the pre-amplifier through the top surface of each transducer. As seen in figure 19, photos of this top surface show no obvious degradation of the pre-amplifier circuit board after 178,000 pressure cycles.

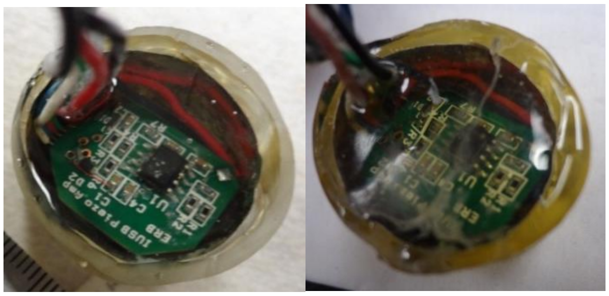

Figure 19) Before and after photos of CuFlon circuit board

The photos above show a transducer before pressure cycling (LEFT) and after 178,000 pressure cycles (RIGHT).

Before pressure cycling occurred on any of these three transducers, each was exposed to a noise source, attached to the oscilloscope, and power spectra were taken. The noise source functioned by forcing air through a brass pipe with a brass cap. Unlike the noise source mentioned earlier in this document, this cap had multiple orifices drilled in such a way that each path that the air could take intersected in the center of the cap. This was done in an effort to generate more noise in the high frequency regime. A regulator and a pressure gauge were installed on this noise source to monitor and control the air pressure. Each time a transducer was exposed to this noise source, care was taken to ensure that the air pressure was fixed at 7 psig, and that each transducer was one inch away from the source. Since the transducers were easily removed from the pressure vessel, this exact procedure was easily replicated after 178,000 pressure cycles. These measurements allowed for a very clear comparison of each transducer's performance before and after pressure cycling. The next three figures display these "before and after" power spectra for each of the three transducers. The associated unit number is noted below each plot and the number of pressure cycles which the transducer has experienced is represented by the displayed color scheme. For all spectra, the vertical axis is acoustic intensity, expressed in decibels, and the horizontal axis is the sound frequency, in Hertz.

🟪	0 pressure cycles
🟦	178,000 pressure cycles

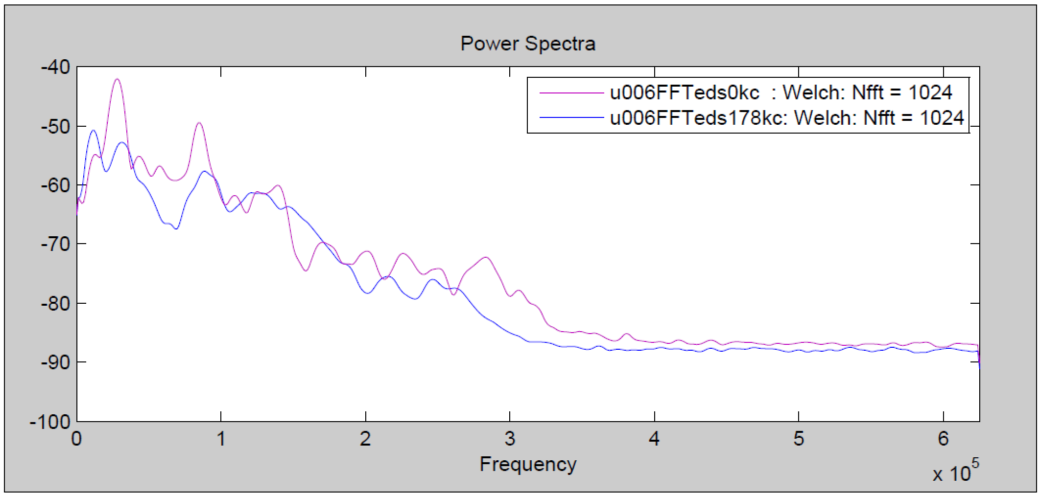

Figure 20) Power spectra for unit 20

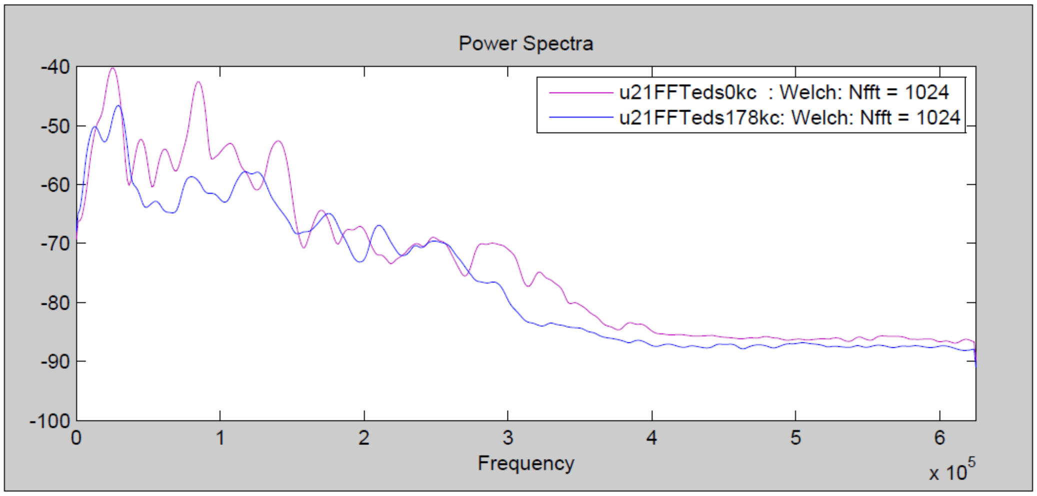

Figure 21) Power spectra for unit 21

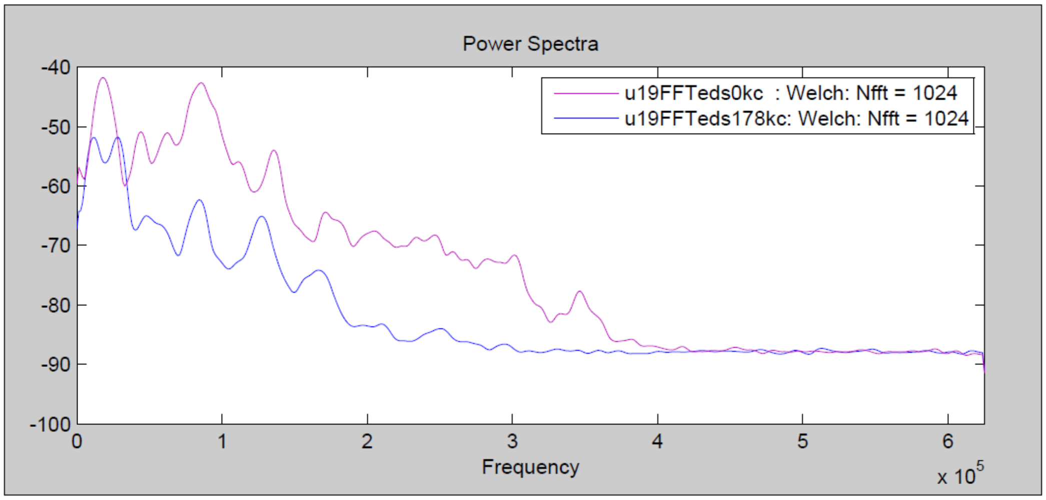

Figure 22) Power spectra for unit 19

The first two plots, showing units 20 and 21, display similar degradation, mostly in the high frequency regime. It was expected that these two units would react similarly to pressure cycling because they were constructed to be identical. While it is certain that some degradation in frequency response is occurring for these transducers, it is not known at this time what is the cause of such degradation.

The last plot in this section, showing unit 19, is dramatically different from the first two. This is likely due to the fact that unit 19 was not constructed in the same manner as the other two units. During the construction of unit 19, a thick layer of “Loctite Superflex” (#59530) silicone RTV was applied directly to the ceramic piezo element of the transducer. This layer of RTV can be seen below, in figure 23. Aside from this extra step in the construction process, the rest of unit 19 is identical to units 20 and 21.

Figure 23) Unit 19 during construction

The photo above shows the layer of RTV applied around the piezo of unit 19.

It is not known by what mechanism the silicone RTV degrades the frequency response of the transducer. It is only clear that this transducer, with a specific type of silicone RTV inside, experienced a much greater change in acoustic sensitivity, after many pressure cycles. More tests would need to be carried out to conclude if the RTV layer is the true culprit of this degradation, and not some other fault within unit 19. Also, other various types of RTV should be tested to conclude if this effect is present with all silicone RTV, or only the #59530 used on unit 19.

Conclusions

Pressure cycles earlier than 40,000 are not displayed in the power spectra shown in the “lifetime data” section because those measurements were taken with an air pressure of 40 psig in the noise source. All measurements taken at or after 40,000 cycles were done with an air pressure of 20 psig. Therefore displaying these earlier spectra on the same plot would be misleading. This means that the measurement taken at 40,000 pressure cycles becomes the baseline measurement which all future measurements are compared to. Since the baseline measurement was taken at 40,000 pressure cycles, what is displayed in the plots under the “lifetime data” section is the transducer performance over 126,000 pressure cycles. The acoustic transducers which were installed on the COUPP detector for the first deep deployment were only subjected to 96 pressure cycles before they were approved for use in the detector[15]. The transducers with CuFlon pre-amplifiers have been subjected to more pressure cycles than any other transducers have in the past and each one is still fully functional, displaying only minor degradation. Any decline in the quality of performance would be seen by looking for variations between the colored lines in the power spectra. The power spectra over time for a robust transducer would appear as only one solid line, where every new measurement is exactly the same as the last. Most of the measurements presented here overlap to the degree that it becomes difficult to discern individual colors. This indicates that the acoustic transducers constructed with CuFlon pre-amplifiers will still function after 166,000 pressure cycles and that they will display only minor degradation after 126,000 pressure cycles. In the real experiment, a maximum rate of around 20 cycles per hour will occur. This corresponds to about 14,400 cycles per month or about 172,800 cycles in a full year of continuous data collection. It should be noted that these three acoustic transducers continue to function to date. It would appear that much more pressure cycling will need to be done in order to discover the full lifespan of acoustic transducers constructed in this fashion.

One might also conclude from an initial and final comparison that the method by which COUPP attaches transducers is not as sensitive of an issue as was previously thought. The electrical connections within the pressure vessel are less resistant to glycol as those present within the COUPP detectors. A simple solder joint, covered by adhesive lined shrink tubing was shown to withstand at least 178,000 pressure cycles within the pressure vessel. If COUPP makes this same connection, and coats the solder joint in a J-B Weld epoxy before applying shrink tubing, it should be just as robust as the connection within the pressure vessel. Also, one can conclude that any connectors present within the outer vessel of the detector would require regular cleaning because material was found building up on the exposed connector pins present within the pressure vessel. It is not clear at this point whether or not the addition of a silicone RTV layer around the piezo would increase the overall sensitivity of the transducer. The measurements described in this document seem to indicate that the addition of RTV within a transducer accelerates any degradation to the frequency response of the transducer.

For future tests of acoustic transducer response to pressure cycling, some improvements could be made to the procedure described in this paper. Ideally, all measurements should be taken under the same conditions. As mentioned above, the air pressure in the noise source was changed after pressure cycling had begun. Had this change not occurred, there would have been measurements reflecting transducer response over 166,000 pressure cycles instead of only the 126,000 pressure cycles shown in the “lifetime data” section. The number of pressure cycles between measurements fluctuates quite a bit for the data presented in this paper. Given the high rate at which the PVS is capable of cycling the pressure in a vessel, collecting data every 10,000 pressure cycles is recommended. Achieving intervals smaller than this recommendation is not practical because it would likely require multiple data collections in one day. This is because the PVS completes about 10,000 pressure cycles in one day. Also, because COUPP attaches their transducers to a quartz surface, it would be more practical for a quartz surface to be present in each pressure vessel used at I U South Bend. Such a surface would have likely prevented the transducers described in this document from becoming detached from the pressure vessel.

To improve on the search for dark matter, detectors like the one used by COUPP will be made more sensitive and will collect data for longer time intervals. This is why it is important for acoustic transducers to be constructed which can withstand constant pressure cycling for months or even years. The procedure described in this paper yields a great deal of confidence regarding the longevity of the acoustic transducers created with CuFlon pre-amplifiers. They have already proven capable of withstanding months of pressure cycling without failure. It is likely that more time in the PVS will prove that they can also tolerate years of pressure cycling.

Acknowledgements

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