Capwell

MEAM 445/446 Final Project Report

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Abstract

Capwell captures and disposes of methane escaping from abandoned natural gas wells in a quick and inexpensive manner.

Approximately 60% of the nation's 3.3 million abandoned oil and gas wells are not properly plugged, resulting in a constant release of methane and harmful chemicals into the environment. Abandoned natural gas wells constitute 5-8% of Pennsylvania's annual methane emissions. Methane has 86x the global warming potential of carbon dioxide, making it a critical target in effectively combating climate change. The current process for plugging wells is slow and expensive. Hundreds of feet of underground well casing must be removed, new casing must be installed, and cement must be poured into the well. This process takes months and costs $68,000 on average. Capwell plugs these wells at the surface, sealing the well with our proprietary cap, filtering methane for toxic gasses, and converting this methane to CO_2 via flaring. Our solution costs $6,000 and can be installed in one day. With Capwell, the $4.7 billion allocated to plugging abandoned natural gas wells by the federal government can cap 40% of wells in the US instead of the 3.5% that the antiquated method can plug. To take on this task, we have researched the problem extensively, assembled a team with a breadth of applicable talents, and enlisted advisorship from leading experts in academia, industry, and the government. Capwell has been validated by these stakeholders. We have built and tested a scaled prototype on a model well and are currently developing v2.

Table of Contents and Table of Nomenclature

I. Introduction

Communicate the need your solution addresses, the stakeholders served, sufficient background to historically and/or technologically frame the problem and existing solution domain, prior or related work and/or solutions and their unsuitability to address stakeholder needs, how your work extends the solution space, and (if applicable) how your solution fits into a larger ecosystem.

According to the US Environmental Protection Agency, more commonly known as the EPA, the population of orphaned and abandoned wells in 2021 was about 3.4 million, with around 2.7 million consisting of oil wells, and 0.6 million consisting of purely gas wells. Only about 60% of such wells have been plugged, resulting in more than 2 million known wells throughout the US that have been abandoned while unplugged [1, p. 231]. Such wells, some of which have been abandoned since the late 1800's, have been leaking harmful greenhouse gasses and chemicals such as methane and benzene into the surrounding environment and atmosphere since their birth [2]. In 2019, abandoned and unplugged oil & gas wells in the US emitted 263 kilotons of methane into the atmosphere. Thanks to the outdated regulations for plugging wells, lack of financial incentive, and extremely costly solutions (often ranging from an average cost of $33,000 per well to severe cases surpassing $425,000), this issue of abandoned wells and their contributions to greenhouse gas emissions will continue to proliferate.

The Environmental Protection Agency (EPA) estimated that unplugged abandoned wells emitted more than seven million metric tons of carbon dioxide into the atmosphere in 2018, which is the equivalent of about 16.2 million barrels of crude oil consumed. Meanwhile, a separate study conducted by esteemed orphaned well researcher Mary Kang and a team of other researchers estimated that carbon dioxide emissions from such wells were actually 20% higher than EPA estimate. Arguably worse is the constant leaking of methane gas from these same wells. Methane is a greenhouse gas around 80 times more potent than carbon dioxide within a 20 year span in the atmosphere [15]. In the state of Pennsylvania, methane emissions from abandoned and unplugged wells represent 5% - 8% of total methane emissions state wide, with corroborating results coming from other states with significant concentrations of oil & gas wells such as Texas and Oklahoma. Beyond methane and other greenhouse gas emissions from these wells contributing to global warming issues and climate change, a significant portion of the gasses leaking from abandoned wells are toxic, highly flammable, and have had catastrophic effects on surrounding communities. In 2016, a school in the town of Midwest, Wyoming was forced to close its doors for more than a year following teachers and students smelling gas-like odors as a result of carbon dioxide levels being more than 20 times higher than recommended. The source was traced to a nearby abandoned well which was leaking carbon dioxide along with high levels of benzene, a known carcinogen. Other communities have not been nearly as lucky. In April of 2017, two Firestone, Colorado residents were killed when their home mysteriously exploded. The explosion was traced to high and unstable levels of butane and methane which found their way into the basement of the home from a nearby abandoned natural gas well and associated pipelines [10]. The imminent risk that leaking abandoned oil and natural gas wells pose on local communities as well as the world is incredibly evident. As headlines such as these have continued to surface, the issue is slowly making its way to policy makers, where an increased push to find a solution through increased funding has now begun. Governments across the world and oil & gas corporations are making pledges to cut methane emissions. The 2015 Paris Accords represented a united effort by countries to lower emissions; companies such as Shell, ExxonMobil, and Saudi Aramco have all promised to have "near zero" methane emissions by

2030; and President Biden just passed an infrastructure bill allocating $4.7 Billion in funding for plugging abandoned wells [18] [19]. These promises from countries and companies have fallen short in the past and need tangible solutions to drive real progress in the space. “Current levels of climate ambition are not on track to meet our Paris Agreement goals,” says Patricia Espinosa, the Executive Secretary of UN Climate Change. However, with the recent funding turning the tide from promises to action, Capwell can help in our urgent fight against climate change.

I.X Social Impacts of the Solution

As a subsection of section I, describe how your solution meets specified needs with consideration of a) public health, safety, and welfare, b) global, cultural, and social factors, and c) environmental and economic factors. (a), (b), and (c) may not apply to all project efforts. For any considerations (a), (b), or (c) that do not apply, indicate so with justification.

Capwell's impacts are broad and far-reaching. Successful implementation of Capwell would bring with it significant reductions in health and safety risks, notable improvements to environmental concerns and downtrends, and economic benefits due to the alleviation of the burden of these wells. Due to the sporadic and largely unmapped nature of abandoned oil and natural gas wells, Capwell's impacts can be noticed in nearly every region of the United States, from cities to farmlands to suburban neighborhoods.

By successfully plugging abandoned natural gas wells, Capwell will prevent further greenhouse gas emissions. The methane emitted by these wells creates dangerous, combustion-prone environments while simultaneously leading to adverse health conditions in local communities. Asthma, for instance, is one such physical ailment that sees a high correlation to these emissions.

Notably, reduction of greenhouse gasses will also help stabilize climate change. Rising emissions are the leading cause of climate change and associated extreme weather events. By taking the initiative in cutting away at these methane emissions from the source, we can start truly combating climate change and the havoc it wreaks on global communities. Economically, these measures will eliminate or reduce associated expenses due to floods, forest fires, or other atypical climate-induced catastrophes. By creating a solution which reduces the cost of plugging tenfold, governments will be able to solve this problem with less money and put taxpayer dollars to other uses.

The health and safety, environmental, and economic benefits of Capwell make it a no-brainer. We must continue developing this system for implementation across the United States. With Capwell, the United States can be a role model for the rest of the world to follow in emissions reduction.

II. Characteristics and Constraints

Communicate the quantitative and qualitative characteristics demanded by stakeholder needs. Justify the characteristics. This section may draw from stakeholder interviews, polls, and canvassing and may reference existing solutions and the limits of physics.

Existing Solutions and Constraints

Discussions with government, academic, and corporate stakeholders have provided us with key insight into the current state of plugging abandoned and orphaned oil and natural gas wells. This process is an expensive, timely, and involved one. Governmental regulations dictate and require a very specific method of plugging wells. Existing or residual well casing must be fully removed, new well casing must be installed in its place, and cementing must take place at every rock formation layer. Oil and natural gas wells are often located in awkward locations, such as in neighborhoods or under power lines, and it can be difficult to set up the equipment necessary for such operations. This adds to the cost and complexity of this well-sealing process. Due to the complications involved with this process, hundreds of thousands of wells are left unplugged and poorly maintained in Pennsylvania alone. Discussions about this issue with stakeholders have highlighted the need for an inexpensive, unobtrusive, quick, and reliable method of plugging these wells so as to reduce the harmful effects of their emissions on human and global health.

Required System Characteristics

Affordability

I. Affordability is a major factor in the consideration of our potential solution. In order for our solution to capitalize effectively on governmental contracts, it must be approximately 1/10th the cost of existing well-plugging methods.

Reliability and Effectiveness

II. This decrease in cost must not come at the expense of reliability and effectiveness in reducing emissions. While the complex cementing process described above remains the only governmentally approved method of permanently plugging abandoned or orphaned oil and natural gas wells, discussions with stakeholders have indicated that regulatory change may be on the horizon. Government officials have indicated that they would flex the current regulations for a band-aid solution such as ours, however we still want to meet the stringent 100% methane capture requirement.

Modularity and Portability

III. The components of the final system must fit in the bed of a truck. This will allow for easy deployment of our system to various locations across the state and nation. Due to the various conditions of wells, our system must be modular so subsystems can be swapped out for more robust or less robust ones when needed. For example, if a certain well emits high quantities of hydrogen sulfide, then we may need a larger scrubber.

Scalability

IV. System components must allow for and facilitate widespread implementation of our device. Such scalability considerations play a major role in the decision to flare collected methane as opposed to capturing, purifying, and storing. We want to be able to roll out Capwell quickly and at high volumes, so off the shelf components are key. Our autonomous solution limits human interaction with our system and allows us to scale.

Ease of Installation and Maintenance

V. Unlike existing methods, our solution must be easy to assemble and deploy. We aim to have installation require at most two individuals and take only a single day. Sensors must also be installed to allow for remote monitoring of the health of the system and to determine when maintenance visits should take place. We have planned for yearly visits to take place to our sites just to check up on the parts and replace the scrubber.

II.X Design Impact of Standards

As a subsection of section II, describe and cite engineering standards, codes, specifications, and technical regulations that informed and/or constrained the solution. Interpret how these standards affect system design and performance. Most projects demand awareness of 5+ critical standards.

There are six main areas of engineering standards to focus on in addition to the general considerations. These areas correspond to the major features of our solution: abandoned wells, gas and fluids, gas collection, safety hazards, environmental protection, and solar energy. Given the complexity of our solution, rapid change in the current industry standards, and growing potential for significant change in these standards over time, the following overview highlights the most critical engineering standards, codes, specifications, and technical regulations pertaining to the design, development, testing, and implementation of the aforementioned design characteristics.

Good Samaritan civil immunity (Title 42)

Title 42, Good Samaritan civil immunity, plays a key role in the development of our solution. We will be allowed to implement and test our solution so long as (a) we are not looking to make money and (b) our efforts to improve the environment remain focul to our work. This gives us amnesty in designing and testing an innovative solution to resolve the issue of abandoned wells.

International Fuel and Gas Code (IFGC)

The above IFGC standards outline the various components of gas collection as administered by the International Code Council. The IFGC covers regulations, gas piping installations, key components (e.g. chimneys and vents), design guidance, as well as safety protocol. This code will be useful in our efforts to design our gas collection system so that it follows the internationally accepted standards. More specifically, our system will have to route the gas into piping designed according to the sizing methodologies detailed in Chapter 4. Additionally, we will need to find the optimal ventilation option.

Fire Protection

As published by the National Fire Protection Association (NFPA), the National Fuel Gas Code (NFPA 54) is the oldest standing model fuel gas code in existence. Alongside the Fire Code (NFPA 1), this document covers rules and requirements for the design and installation of fuel gas piping systems in homeless and other buildings. Thus, we have set the parameters of our solution (i.e. the flaring component) following these guidelines in order to achieve the optimal adaptability, especially given that abandoned wells can be in a wide range of locations and environments from residential basements to public spaces**.**

Well Abandonment Site

This resource [BSEE-0124 250.1721] provided by the Bureau of Safety and Environmental Enforcement outlines the standard steps taken when temporarily abandoning a well, which informs how we frame our problem and scope our solution. Additionally, in terms of reclamation, This specific code [U.S. Code § 15907] addresses orphaned, abandoned, or idled wells on Federal land highlighting key differences amongst the three.

We also took into consideration the Solid Waste Management Act (SWMA) to ensure we handle any potential centralized impoundments, storage of production fluids from conventional wells, or alternative pit liners accordingly. Lastly we had to ensure we thought ahead about a Preparedness, Prevention and Contingency (PPC) plan prior to generation or storage of waste onsite.

Gas Collection

Regarding compressed gas cylinders, this specific set of codes listed in the OSHA's spreadsheet helped us Identify common oversights of safety issues as well as discuss the standards for gas management and gas release. While these regulations largely address cylindrical pressure vessels, the guidelines also mention ventilated boxes as an alternative (1926.350(f)(6)). Another important code mentioned deals with transporting, moving, and storing compressed gas cylinders (i.e. the configurations, the orientation, and the climate control necessary to avoid potentially hazardous situations (1926.350(a)).). In our case, our design calls for our pressure vessel to be an outsourced component. This meant that we had to inspect the parameters in our pressure vessel during the procurement process to ensure the subsystem satisfies engineering standards.

Additionally, we have referenced both the ISO 10431:1993 Petroleum and natural gas industries — Pumping units and Compressed Gas Association, Inc. (CGA) "Safe Handling of Compressed Gasses", to guide our gas management throughout our system.

Solar Energy

In the latest set of guidelines, ASCE [7-16] The American Society of Civil Engineers (ASCE) makes a few updates that change the solar landscape and its opportunities. As it stands, the main drivers for this change are the seismic and wind loads. Naturally, these nuanced regulations are important to understand due to consequences in costs and feasibility (solar energy plays a significant role in our solution). More specifically, even just new wind maps can significantly affect design criteria. This also includes rules on whether or not a building is eligible for building on the roof.

III. Design, Engineering, and Realization

Communicate the design, optimization, and realization of the system-level solution and subsystems. This section should reveal the designs that were considered, why the leading solutions were selected, the design, engineering, experimental efforts, and manufacturing that underpinned selection and realization of the system. You must show that you made a conscientious effort to propose, examine, compare, and select from a number of legitimate alternative concepts for your overall system design and critical subsystems. When presenting experimental tests or simulations, describe the questions the test was designed to answer, describe the test procedure, show the results, preferably as graphs or visuals (tables of results may also be included in the appendix), describe the analysis methods, and discuss the conclusions drawn and the implications of the results. Do not leave interpretation to the reader.
This section should be a focus of the report and may leverage down-selection tables, sketches or images, diagrams, etc. that visually support important information.

System-Level Solution

The idea of preventing methane emission came from the personal experience of Walter Hubsch. Being from the Pittsburgh area where abandoned wells are rampant, Walter had a deep personal connection to the problem. When proposed to the team, each member saw the impact the project could make and immediately bought in. Once accepted, the team immediately started to consider what the system would look like. The system level solution centered around how to effectively seal and prevent methane emission into the atmosphere. The original solution consisted of only three subsystems: sealing, compression/vacuum, and storage. The initial plan was to pull vacuum in the well and actively suck the methane out of the well. However, after speaking with stakeholders, it was determined this system would not work as wells are often filled with water, oil, and other material. The sealing design was then shifted from an active vacuum design to a passive diffusion design. This means that the natural rising of methane will be the primary driver for the methane to enter the system. Another initial idea that had to be changed was what to do with the methane once it was collected. The first idea was to store the methane then sell it to energy companies to help our profits. However, after speaking to members of the oil and gas industry, this was quickly ruled out as this would make our company legally a producer. This causes a large amount of bureaucratic red tape as well as a high cost in tax and bonds to the government. An alternative solution therefore had to be found that would not cause us to be viewed as a producer in the eyes of the government. From these initial ideas and stakeholder outreach, the final system level solution was determined to have five subsystems: solar, sealing, scrubbing, compression/storage, and flaring.

Sub-System Design

The sealing subsystem was the most custom part of the whole system and was where we focused the majority of our design efforts. A few different possible solutions were considered and the most effective one in the determined categories was the one chosen for development. This downselection can be referenced in the chart below.

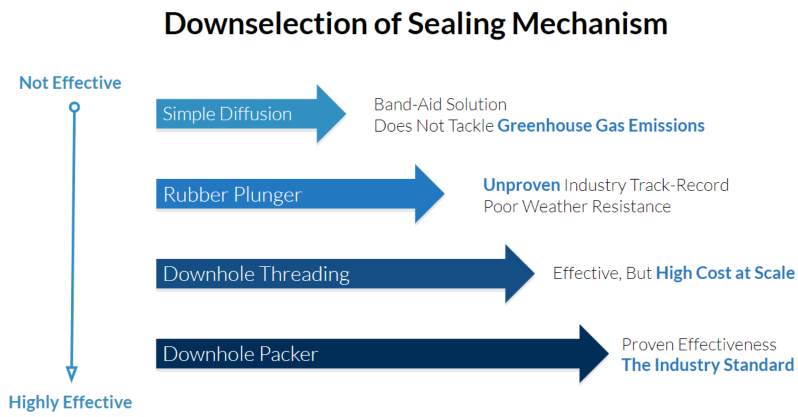


Figure 1. Down Selection Chart for Sealing Mechanism

Simple diffusion allows for the methane to rise from the wellbore and be stored in an above-surface containment vessel. Ideas that were considered were a tent and an inflatable soft tank. This is a more advanced version of the plastic bag method currently in use by the Pennsylvania Department of Environmental Protection. The main issues with this method are the lack of durability, the low containment rate of methane, and the susceptibility to tampering.

The rubber plunger method involves pressing a conical rubber device into the wellbore to create a seal. This idea came from the plungers used in chemistry labs to seal test tubes. This method was deemed to be too vulnerable to weather wear in addition to being relatively unproven. Additionally, we were concerned about how removable it would be. We need Capwell to be easily removable so that cementing crews can permanently seal the well down the line. The plunger method would be difficult to remove and was ruled out.

Downhole threading involves cutting threads into the top of the casing and screwing a thread onto those threads. This would be a very effective method, however the size of the machine needed to cut those threads and the power needs would be too much for our pickup truck sized solution. This makes it too expensive at scale to be a real solution.

The downhole packer solution was based on the downhole packers that are used in the oil and gas industry to create seals deep dowhole to pump oil or gas out of the well. We adapted this for a surface level solution that rests on the ground and has inflatable bladders to seal against the walls of the casing. This solution was selected due to its use in industry, effectiveness in sealing, and fitting our constraints like ease of transport.

The next major subsystem we down-selected on was the collection/disposal of methane, as shown by the following figure.

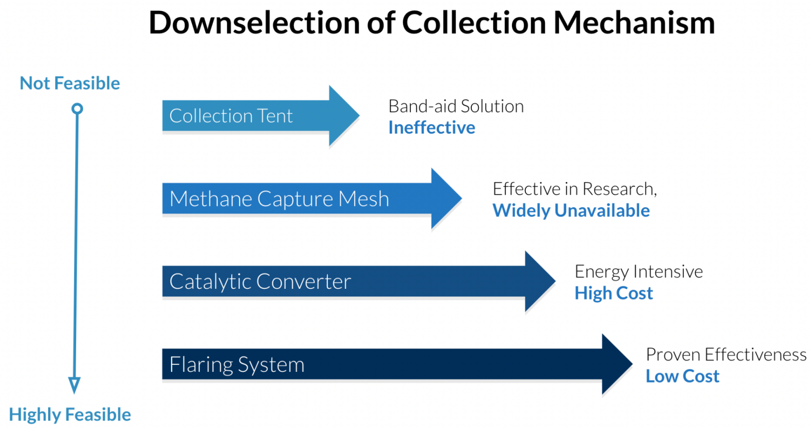


Figure 2. Downselection Chart for Collection Mechanism

The collection tent is a combined solution with sealing as it both seals and collects the gas. Due to the issues listed previously, this solution is not ideal. It also doesn't solve the problem of disposing of the gas so we quickly ruled it out.

The methane capture mesh is a new technology that can capture methane very efficiently in the interstices of the mesh. This allows for a large amount of methane to be stored in a small volume. Our concern with this technology is that it is still in early research stages and may be difficult to scale. We didn't want to risk putting technology on our device that hadn't been tried and tested by the oil and gas industry so we ruled this idea out.

The catalytic converter takes methane and converts it into carbon dioxide. Carbon dioxide's lower environmental impact made this an attractive option, however catalytic converters require very high temperatures to work. This would make our energy needs too high to be met in the field.

Flaring, combusting the methane and converting it into carbon dioxide in the process, is the standard in the oil and gas industry. It is cost effective and reduces the impact to the environment by 80x [15]. It can be implemented quickly and safely due to how standard it is. This made it the clear choice for our purposes.

For our scrubbing and compression/storage subsystems, there was less debate about the possible options. Industrial hydrogen sulfide scrubbers are overkill and our compressor debate centered around what brand and model we should buy.

For the hydrogen sulfide scrubber, we wanted to have the most cost effective and simple solution possible. Industrial scrubbers are too complicated and expensive for the low amounts of scrubbing we need done. Steel wool is the "dumb" alternative, doing its job in preventing hydrogen sulfide from reaching the environemnt at a low cost. The steel wool has to be replaced once a year at a maintenance cost of less than $500.

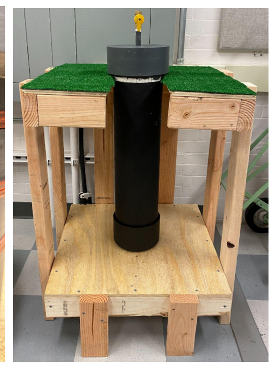
The compressor was chosen due to its modularity and ability to interface with other components. In addition, it needed to be battery powered so that it is rechargeable by the solar array. The off-the-shelf compressor that best fit all these needs was the Milwaukee M18 two gallon quiet compressor.

System Validation

We first validated the individual subsystems before assembling them all together and validating the full system. Each subsystem had certain tests to make sure it could function properly individually, and with the rest of the system. If the test wasn't passed initially, we tried certain alternatives and got creative with how we could solve the problem. Each of the following sections outlines our testing procedure, hurdles, and eventual validation for each subsystem.

Well Sealing

When validating our well sealing subsystem it was important for the team to replicate all types of pressures that would be seen at the wellhead. Our team chose to test at various pressures up to 50 PSI_g since we only expect to see a maximum internal system pressure of 30 PSI_g before turning on the compressor for flaring. This represents a factor of safety of 1.66. Successful validation of the well sealing subsystem would entail having no leaks at the mock well interface. This was done via the soapy bubble test. The soapy bubble test is a test procedure commonly used in the oil & gas and automotive industries to test for leaks. Soapy water is sprayed at an interface and bubble formation is looked for. If bubbles form, there are leaks at the interface. Otherwise, the system is sealed.

Figures 3.1-3.3. (Left to Right) Demonstration of the Soapy Water Test, Ripped O-Ring, Final Cap on Mock Well

We ran the soapy water test for our well sealing validation, but ran into some problems during the sizing of our downhole packer's O-Rings. If the O-Rings were too small, gas could easily escape, and if the O-Rings were too large, the material could rip. Through trial and error, we were able to correctly size the rings and pass the soapy water test. In order to give our sealing system an additional level of safety and robustness, we applied JB Weld epoxy to the outer interface. This was our failsafe mechanism to ensure that we truly had no leaks. If implemented on a real well head, we believe using epoxy would be especially useful as an extra safety measure which would help ensure the integrity of the well sealing system across all environmental conditions.

Compressor

For our compressor subsystem, we chose to purchase the Milwaukee M18 FUEL 2 Gallon Compact Quiet Compressor. Given that it was an off-the-shelf part, we were confident in the compressor's ability to function as desired. However, we wanted to ensure that the compressor could fit into the rest of our system with no leaks and correct gas flow. Specifically, we wanted to have no leaks present at the intake of the compressor and wanted the compressor's flow regulator to reliably output a desired PSI. To test this, all pipes and fittings from the compressor were connected to the wellhead and hydrogen sulfide scrubber applying PVC Pipe Cement at each interface. It was then observed that the compressor intake did work as expected, with only minimal leaks at the intake. This was due to the fact that the intake to the compressor had proprietary threads that Milauwkeee did not disclose when we contacted them. We couldn't use JB weld because of the possibility of it making its way into the compressor as it was curing, so we decided to accept this limitation.

To test the reliability of the built-in flow regulator, we connected the quick connect output to an analog pressure gauge which verified that the flow regulator could be trusted to produce values with a high degree of accuracy. This test in particular was helpful to inform our sensor calibration procedure.

Control System Validation

Our control system consisted of a pressure sensor, a vacuum sensor, and a ball valve actuator. We defined test success here as being able to accurately read pressure from the sensors and control when the valve opened and closed. To do this, we set up the circuit shown in A-2. In Arduino, we were able to convert analog readings from the pressure sensors to PSI_g readings. Using the test setup found in A-3, we were able to connect the test setup to our compressor and use the built-in flow regulator to successfully calibrate the pressure and vacuum sensors at various PSI. The compressor was able to pull -10.8 PSI of vacuum (73.4% of full vacuum).

For control of the ball valve actuator, we initially setup the circuit with a switch to validate the system. In order for this to be controlled by an Arduino microcontroller, we needed a way to control the system independently. In this case, we used an H-Bridge to control our valve which proved highly successful after much trial and error with the circuit setup.

Additional Validation

There were two additional subsystems which required validation prior to full scale implementation: flaring and hydrogen sulfide scrubbing. Given time, resource, and safety constraints for the scope of this project, our validation and testing for these specific subsystems was limited. Firstly, in order to test our flaring subsystem, it was required that our team release and combust methane gas. Due to the hazardous nature of the procedure, safety concerns were raised by the instruction team for this test. As a result, we tested our full system using Helium to emulate a gas that was lighter than air flowing through each stage of our system. As flaring has been understood and used in the oil and gas industry for over a century, we anticipate no issues in finding an off-the-shelf flare to validate our flaring system at a later date.

Likewise, it was determined that testing with hydrogen sulfide for the scrubbing of the sour gas released from the wellhead was too dangerous. Classified as the most common cause of workplace death by OSHA, inhalation of hydrogen sulfide gas was a serious safety issue that was unable to be overcome for the validation of the scrubbing subsystem [7]. We are confident in the integrity of the scrubbing system given the wide use of steel wool for biogas scrubbing. Additionally, research supports this decision with studies finding that steel wool can remove up to 97% of hydrogen sulfide from a system [14]. More information on methane flaring and hydrogen sulfide scrubbing chemistry can be found in equations #1 and #2.

Prototyping

The majority of the custom work took place in the design and manufacturing of the packer system. This piece was turned out of 8in PVC with grooves slotted for the silicone o-rings to seal against the mock well. O-rings were chosen instead of inflatable bladders due to the ease of design. This was acceptable for a proof of concept, however for the full system, we will utilize the bladders. The main troubleshooting required on the sealing device was the sizing of the rings. Even with an optimized ring size, there was still a small amount of leakage at the interface of the well and packer. We therefore had to apply some epoxy along that edge. Once fully cured, the sealing system no longer had any leaks. The plumbing of the system also required some fiddling to seal properly. The PVC pipes that connected the different systems were sealed with PVC cement. This did a good job of actually holding the pipes together, but did not necessarily create an airtight seal. Therefore tests had to be performed on each seal to determine if there were leaks. Once found they were addressed with epoxy.

Another unexpected design challenge that was found during assembly was that there was no designed way to keep the mock well elevated and upright. The stand needed to be off the ground because the inlet for the helium into the well was a male quick connect fitting that came out of the bottom of the well. Therefore space had to be left for the female fitting and hose to pass underneath. We constructed a stand to fulfill these requirements.

IV. Final System Form

Communicate the final system form, (if applicable) system in context of a larger solution ecosystem, system function(s), and stakeholder interaction with the system.

Figure 4. Final System Form Render

Background

Our system will be installed on top of an existing abandoned and orphaned natural gas well. It will interact with the wellhead, the exposed part of a well that consists of metal casing and whatever was left behind. We may need to take off any parts that cover the wellhead to access the casing. Well conditions can vary, but all wellheads will have casing sticking out of the ground that we can interact with. We chose to have our cap seal with the well but not exert downward pressure for very corroded and fragile well heads. We may also need to dig around the well and clear the area to fit our system into the casing. The diameter of this casing is ~30in. but can range up or down a couple of inches. Our final cap is undersized, but the inflatable bladder makes up the difference to make a tight seal on the inside of the exposed casing. We will need to clear the area of possible falling hazards, like a tree with branches above our system for example. Our system is enclosed and shouldn't heat up too much so we aren;t concerned about fire hazards here. The reason we don't want debris falling on top of it is because it will cover our solar cell. We are considering changing the orientation of the solar panel for high snow environments, but for now believe that its current setup will perform well in most of the United States. Our system should be able to navigate the common environmental challenges that the traditional process faces such as power lines, small spaces, and remote locations due to our system characteristics considerations.

After the wellhead area is cleared, the cap is installed. The cap is rested on the ground on top of the wellhead and the bladders are inflated until they seal tightly with the well. Our flow sensor box is welded on top of the cap. This measures the amount of methane that is captured and disposed of, and it is available to us courtesy of the Well Done Foundation. The hydrogen sulfide scrubber and pipes are welded onto the system. The pipes then go into an Ingersoll Rand 80 gallon compressor, and from the compressor to an off-the-shelf flare. This must all be welded together on-site. Our control system, computer, and battery are all installed. A shell goes around the full system to prevent tampering, and finally our solar cell sits on top. Capwell can be installed in one day with a team of two people handling the clearing, assembly, welding, and final inspection.

We believe Capwell's characteristics - low cost, quick, modular, portable, sensor enabled, and effective - make it perfect for dealing with the 2 million abandoned wells across the United States. It can fit any well in any condition aside from the extreme outliers.

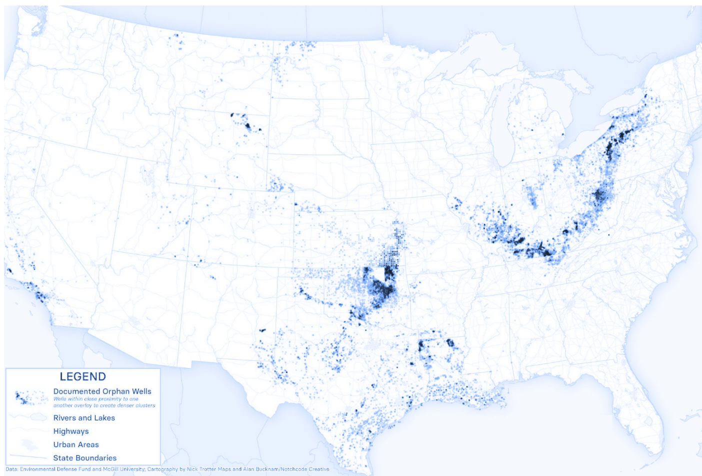


Figure 5. Map of Abandoned Wells Across the United States

System Functions

The Capwell system aims to limit the environmental impact of methane emitted from abandoned and orphaned oil wells. It contains 5 distinct subsystems: sealing, hydrogen sulfide scrubbing, compression/storage, flaring, and solar. The system is powered by a 55W solar cell which costs around $250. The solar needs were calculated given the system power yearly needs given our systems duty cycle, we calculated the size of the solar array based on the solar power that we could expect to receive in Pennsylvania and given these calculations, the solar system will be able to be easily applied to other geographies with large numbers of abandoned natural gas wells - namely Oklahoma and Texas [Table 1, Table 2]. The sealing subsystem consists of the packer which is inserted into the wellbore. The bladders then inflate to create an airtight seal that only allows air to pass through the center rather than escape through the sides. From there the gas naturally diffuses through to the hydrogen sulfide scrubber. The steel wool scrubs the dangerous chemicals from the gas mixture, leaving nearly pure methane to pass through to the compressor assembly. This compresses and stores the gas until a sufficient quantity has been obtained for safe and efficient flaring. This subsystem is necessary as sometimes wells dont naturally produce enough methane to sustain a constant flare. In addition, the quantities that each individual well produces can vary from day to day. With the compressor, flaring can occur with the same quantity and quality of methane each time. The flare converts the methane into carbon dioxide by burning it and emitting the product through a stack. Unfortunately, flaring could not be tested at Penn due to school regulatory requirements. However this will be the first system to be tested once v2 development begins.

System Diagram

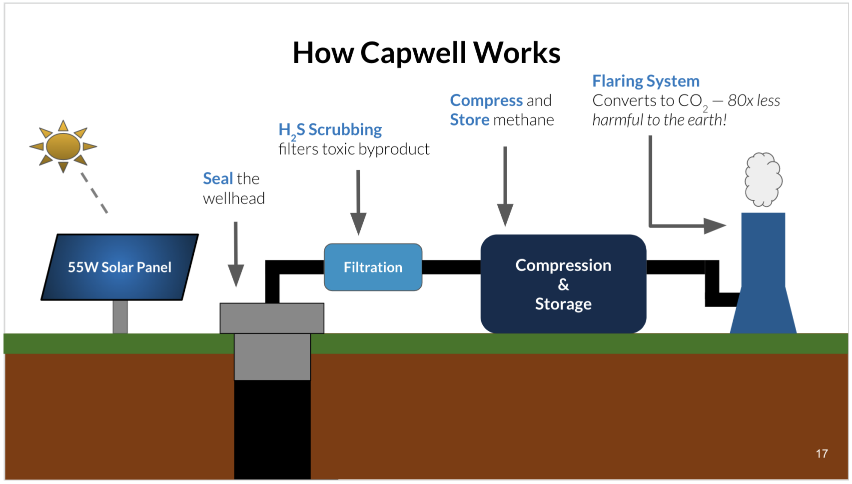


Figure 6. System Graphic

V. System Performance

Synthesize the purpose, results, analysis, and conclusions associated with validation of the overall system in a compact statement. This section may reference information presented in the design, engineering, and realization section if the system performance is a culmination of separate subsystem tests broached in that previous section.

Validation

Once our individual subsystems were validated, we put them all together and tested our full system. The full system test was conducted using helium, a lighter-than-air gas, to show that the gas emitted from our mock well was actually making its way through the system just as methane would in an actual system implementation. We passed helium from a helium tank to our mock well. Then we allowed the gas to enter our system, flowing through the cap and scrubber into our compressor. At the end of the system (before the theoretical flaring subsystem and after the compressor subsystem), a balloon was placed on top of the nozzle and filled with the gas coming out of the compressor. The balloon floated, indicating that the full system was successful and validating the controlled flow of gas through our system. Had the balloon fallen, we would have known there was an issue with the system and that the helium was escaping.

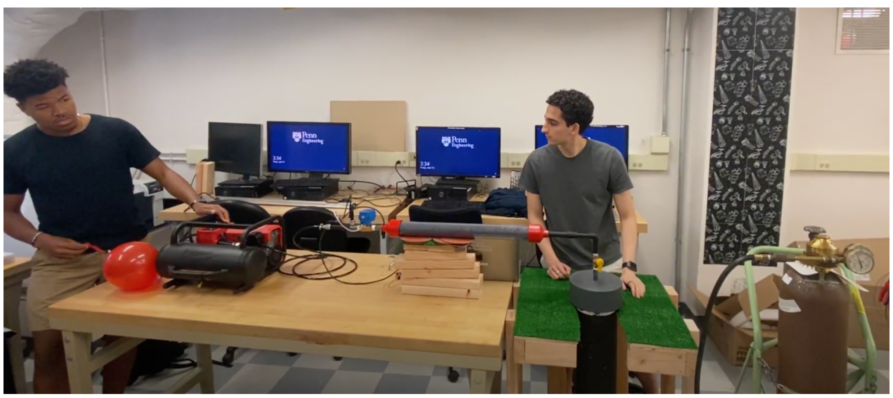


Figure 7. Capwell Validation Setup

Figure 8. Helium Validation

Results

Upon completion of the test, a balloon filled with the gas from the compressor and one filled with air were held side by side. When released, the balloon filled from the compressor immediately rose to the ceiling whereas the air filled balloon predictably fell to the floor. This meant that the system's overall function was achieved, which was successfully capturing gas from the mock well, passing it through the scrubber, and compressing and storing it.

Analysis & Conclusions

Analyzing the performance of our prototype system as a whole, there are a few notable takeaways to discuss and associated extensions which offer key areas for future focus and improvement. While proper gas flow through the prototype system was demonstrated and validated, a crucial future step lies in ensuring fully remote operation of this gas flow and associated pressure regulation, particularly regarding the interplay between embedded electronics systems, pressure valves, and the compressor.

Future system iterations would include a one-way pressure valve at the interface of the hydrogen sulfide scrubbing tube and sealing cap, as opposed to the manually controlled on-off valve included in our prototype. This would allow for one-way, controlled flow out of the well without any troublesome backflow. Additionally, the electronic system that we constructed and validated would be more robust, allowing for full control over the exit valve of the hydrogen sulfide scrubbing tube and respective operation of the compressor. Future testing with such system improvements and adjustments would allow us to better understand critical areas of failure with this proposed final form.

Testing on our sealing subsystem also yielded important findings and highlighted areas for future development. Though our scaled PVC sealing cap was effective in sealing gas leaks on our model well, tolerancing our mock O-rings was largely a "guess and check" process due to the level of precision required and the difficulty of cutting silicone on the laser cutters in the Rapid Prototyping Laboratory. Future iterations of our sealing cap will have two notable changes. First, the size of our cap will be greatly increased and thus the respective manufacturing method for this cap will likely need to change. We propose using aluminum parts that will be cast in a mold or welded together, as this is much more durable for the harsher outdoor environments we plan on installing Capwell. Additionally, minor adjustments will be made to allow for the use of inflatable bladders as opposed to silicone O-rings of a set diameter. This will allow for tight interfaces on a variety of well heads and well conditions.

Other important advances that can be made in future iterations include consolidating the system into a smaller area, constructing a protective cover that would prevent tampering and unnecessary weather-induced wear, adding solar cells which would allow for renewable power generation, and incorporating the Well Done Foundation's flow sensor.

VI. Conclusions and Future Work

Project Review

Capwell's impact is clear. This project can put a significant dent in emission levels and ultimately reduce the impact of climate change globally. In Pennsylvania alone, Capwell's implementation would lower methane emissions by 5-8%, more than two times the amount of methane that comes from our agriculture industry [17]. Our solution is faster, more inexpensive, and just as effective as current plugging methods. After speaking with expert stakeholders, we came to the design choices of a modified downhole packer for our cap, a standard air compressor for our gas storage, and an off-the-shelf flaring device for disposing of the methane. We chose to scale down our system and test with helium for the purposes of Senior Design. This prototype was validated, allowing us to confidently scale up our system. With some key upgrades, Capwell can start fighting climate change, one well at a time.

Design, Validation, & Logistics

The modified downhole packer was chosen due to it being industry standard in sealing to various wellhead sizes and conditions. We chose to implement it on the surface of the well at ground level so make installation easy. We decided to use a standard air compressor after finding various at-home biogas rigs that used them to compress and store methane. Its suction is what moves gas through our system, and its storage tank allows for a steady release of methane when enough has built up. The compression of methane is a plus as it allows us to flare less often, lowering our energy needs. The flaring decision was chosen because it is low cost, effective, and industry standard. Some other technologies like methane capture meshes are promising, but still in early stages of development. Due to time, equipment, and financial constraints, we scaled down our system to ¼ size and built it out of PVC instead of aluminum. Due to safety concerns, we tested with helium, a safe and inert gas, instead of the more combustible methane, and didn't validate our hydrogen sulfide scrubber. As discussed in the previous section, we were able to validate our Capwell prototype with helium, a great first step in proving our system works. We can capture gas, control its flow, and dispose of it. This initial test allows us to confidently scale up our system for real well testing. One key area that was not able to be validated due to safety constraints was the flaring component. We created a possible flaring device inspired by gas barbeques but were unable to test it with a flammable gas. This component of our system is the first one that will be tested when we build version 2 and install it on a real well.

Takeaways & Next Steps

For version two of Capwell, we would scale up, improve, and add in certain components. Our cap would have inflatable bladders to fit a variety of wellhead sizes. The H_2S scrubber and air compressor would both be larger to handle the higher flow rates of gas. Our sensor and control system would be more robust, with methane measurement sensors and a small computer controlling the on-off of our systems. Additional components would include a 55W solar cell to meet our power needs, a 110 Ah battery pack (approx. $200) to store this power in, and an off-the-shelf flare to dispose of the gas. Aside from system level improvements to Capwell, next steps include company formation, intellectual property protection, business model iterations, and a Well Done Foundation partnership and tests. These activities will be taken in conjunction with the engineering development process to bring Capwell to market by the end of the summer.

VII. Statement of Roles

Andrew Lane utilized his oilfield services background to create designs based on stakeholder needs. The downhole packer solution stemmed from his exposure to the current packers used in industry. In addition, he has been vital to creating the CAD of our v1 and v2 system as well as being heavily involved in the manufacturing, assembly, and testing of the subsystems. This includes the machining of the PVC packer, the silicone rings, and various supporting devices used on the system.

Justin Hegar made use of his automotive industry experience and joined the team in the Spring semester. His outside perspective was helpful for the refinement of our ideation process and the down selection to our final system form. This included the addition of a compressor, hydrogen sulfide scrubber, and sensors and valves to the final system. Justin stepped up in a variety of roles including manufacturing, assembly, purchasing, and presentation narrative and aesthetic refinement. He was vital for creating the BOM, engineering drawings, v2 CAD refinement and rendering, and creating test setups using Arduino to calibrate pressure sensors.

Lucien Peach has made use of his research and coursework experience to contribute to a variety of roles within the project. His main focus has been on the manufacturing, assembly, and testing of the sealing subsystem. This involved precision machining the PVC cap, laser cutting the silicone gaskets, and general design and manufacturing of the mock well assembly and related display structures. In addition, Lucien played a key role in creating and synthesizing our v2 CAD, which is included in this report.

Niko Simpkins drew from his experience in integrated product design and mechatronics to contribute to the team's design efforts. His design leadership ranged from presentation and slide composition to circuits and electrical system configuration (i.e. integrating the various electrical components like the three-way ball valve, pressure sensors, and microcontroller). Additionally, he owned the workstream responsible for regulatory compliance, codes, safety standards, and risk analysis. Lastly, Niko is leading the design and implementation of IoT compatibility and network connectivity for the future iterations.

Tomas Pinilla brought his project management experience and team player mentality to the project. He helped the team stay on top of deadlines, divide work up for it to be manageable, and enabled everyone to work together hard and smoothly. He was responsible for driving several key initiatives forward: subsystem downselection, PVC cap machining, BOM creation, part purchasing, system assembly, and poster design.

Walter Hubsch used his interdisciplinary education, experience in infrastructure projects, and personal narrative to further the team’s efforts. His stakeholder outreach was relentless and allowed us to speak with the most important people tackling this problem. His personal narrative gave the project a voice here in Pennsylvania, and he was crucial in communicating the ethos of the project to audiences. Other key areas he impacted included building and testing, powerpoint and report work, business plan creation, BOM refinement, and poster design. One notable impact of Walter on the team was the opportunity to look at the problem from a business perspective, a truly important addition as it allows us to take the project from the classroom to the real world.

VIII. Acknowledgments

Acknowledge all persons other than the team and primary advisor that contributed to or impacted the work by name, professional title, and contribution.

Academic

Dr. Mary Kang - Assistant Professor, McGill University

> Dr. Kang is one of the leading national experts on abandoned and orphaned wells, and played a crucial role in providing us an accurate and detailed description of these wells and the challenges we must consider in designing our solution.

Corporate

Luke Plants - Chief Operating Officer, Plants and Goodwin, Inc.

> Luke has been our advisor throughout the entire year and has served as an invaluable resource in allowing us to understand the complexities of plugging wells via current methods as well as serving as a source of consultation for the dynamics of our proposed solution.

Curtis Shuck - Chairman, Well Done Foundation

> Curtis is a more recent addition to our advisory network. He has provided us with important insight on the well-monitoring efforts that he runs and how our proposed system can fit into the existing sphere of abandoned well maintenance. Going forward, we plan to continue working with Curtis to integrate future iterations of our technology with his systems.

Governmental

Seth Pelepko - Former Environmental Program Manager, Bureau of Oil and Gas Planning and Program Management, Pennsylvania Department of Environmental Protection

> Seth provided us with key information into the manner in which the government handles contracts and prioritizes wells, described the legal considerations we should take into account in planning our solution, and described how upcoming bills and funding would affect the place of our solution in the currently existing field.

References/Citations

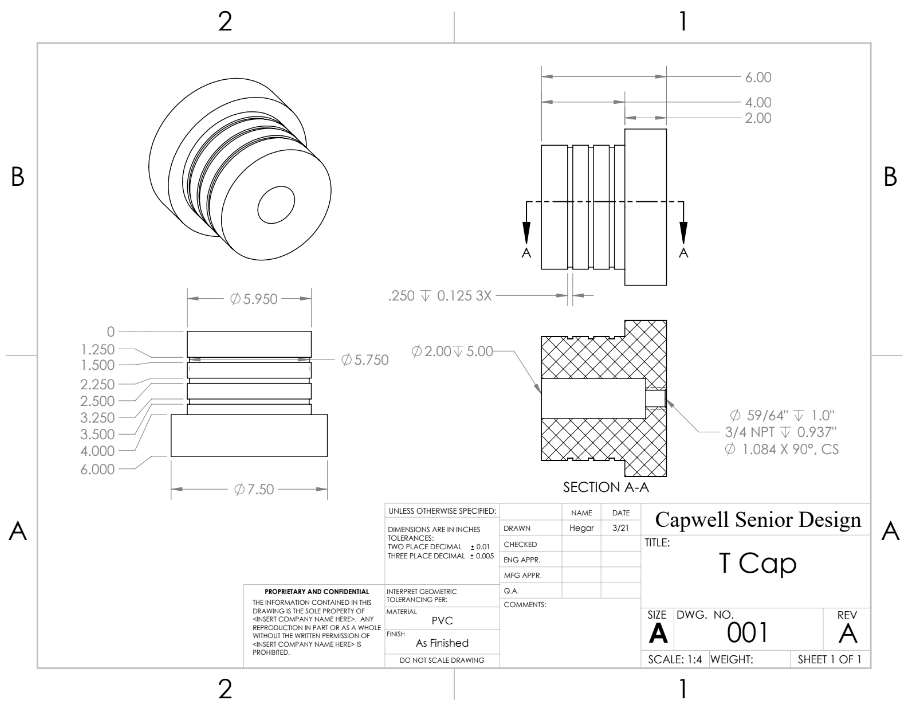
1. Bertrand, S. (2021, August 12). Plugging Orphaned Oil and Gas Wells Provides Climate and Jobs Benefits. Environmental and Energy Study Institute. https://www.eesi.org/articles/view/plugging-orphaned-oil-and-gas-wells-provides-climate-and-jobs-benefits
2. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed Stocker T, et al. (Cambridge Univ Press, Cambridge, UK), p 1535.
3. Cornell Law School. (2020, January 1). 42 U.S. Code § 15907 - Orphaned, abandoned, or idled wells on Federal land. Legal Information Institute. https://www.law.cornell.edu/uscode/text/42/15907
4. Environmental Defense Fund. (2020, January 1). Documenting orphan wells across the United States. EDF. https://www.edf.org/orphanwellmap
5. George, R. (2019, January 5). Fuel Gas Piping Systems and Fuel Gas Codes. PHCP Pros. https://www.phcppros.com/articles/8720-fuel-gas-piping-systems-and-fuel-gas-codes
6. Holland, R. (2016, June 21). DEP Legacy Well Emissions Study. Slide Player. https://slideplayer.com/slide/13128767/
7. "Hydrogen Sulfide Hazards." *Hydrogen Sulfide - Overview | Occupational Safety and Health Administration*, United States Department of Labor, 2022, https://www.osha.gov/hydrogen-sulfide#:~:text=Hydrogen%20sulfide%20is%20one%20of,toxic%2C%20even%20at%20low%20concentrations.
8. Kang, M., Christian, S., & Celia, M. (2016). Identification and characterization of high methane-emitting abandoned oil and gas wells. PNAS, 113(48), 13636-13641. https://www.pnas.org/content/113/48/13636
9. King, H. M. (2020, January 1). Production and Royalty Declines in a Natural Gas Well Over Time. Geology.com. https://geology.com/royalty/production-decline.shtml
10. Pearson, M. (2020, January 1). The Seven Steps Of Oil And Natural Gas Extraction. Coloradans for Responsible Energy Development. https://www.cred.org/seven-steps-of-oil-and-natural-gas-extraction/
11. PIOGA. (2020, January 1). Oil and Gas Regulations. Pennsylvania Independent Oil and Gas Regulations. https://pioga.org/education/oil-and-gas-regulations/
12. Pontecorvo, E. (2020, December 1). Abandonment Issues. Grist. https://grist.org/energy/plugging-abandoned-oil-wells-carbon-offsets/
13. PrivateWellClass. (2017, August 31). How to Seal an Old Well. Youtube. https://www.youtube.com/watch?v=R4bMq1MhiuQ
14. U Riyadi et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 105 012026
15. UN Environment Programme. (n.d.). *Methane emissions are driving climate change. here's how to reduce them.* UNEP. Retrieved May 5, 2022, from https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them#:~:text=Methane%20is%20the%20primary%20contributor,at%20warming%20than%20carbon%20dioxide
16. United States Department of Labor. (2020, January 1). Oil and Gas Extraction. United States Department of Labor. https://www.osha.gov/oil-and-gas-extraction/standards
17. Pennsylvania Greenhouse Gas Inventory Report. (2020, July 1). Pennsylvania Department of Environmental Protection.

https://files.dep.state.pa.us/Energy/Office%20of%20Energy%20and%20Technology/OETDPortalFiles/Climate%20Change%20Advisory%20Committee/2020/Pennsylvania%202020%20GHG%20Inventory%20Report.pdf
18. Browning, Noah. "Major Oil Companies Aim for Zero Methane Emission by 2030." *Reuters*, Thomson Reuters, 8 Mar. 2022, https://www.reuters.com/business/sustainable-business/major-oil-companies-aim-zero-methane-emission-by-2030-2022-03-08/.
19. Newburger, Emma. "Biden Is Sending More than $1 Billion to States to Plug Abandoned Oil and Gas Wells." *CNBC*, CNBC, 31 Jan. 2022, https://www.cnbc.com/2022/01/31/biden-helping-states-plug-orphan-oil-gas-wells-cut-methane-emissions.html#:~:text=The%20funding%20to%20plug%20oil,wells%20abandoned%20across%20the%20country.

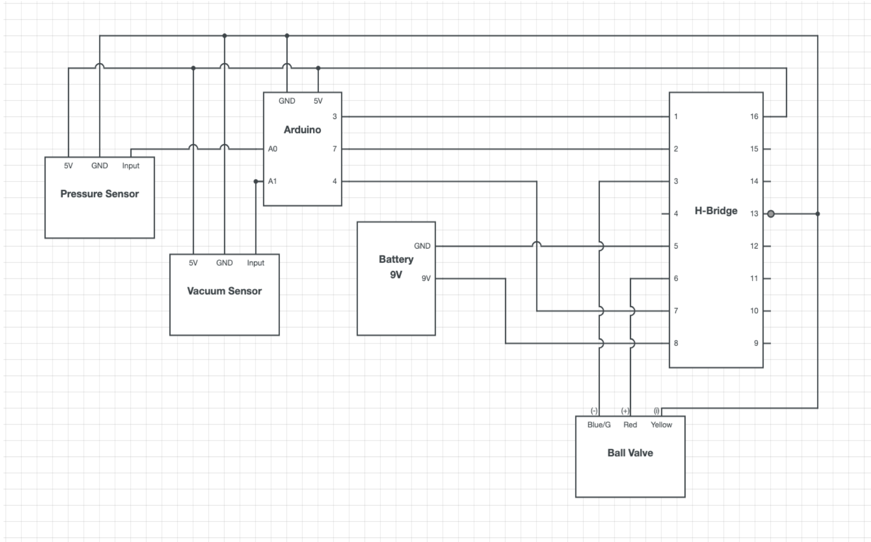
Appendix

Equations:

1. Hydrogen Sulfide Scrubbing Chemistry:
    a. $Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O$
    b. $Fe_2S_3 + 1.5O_2 \rightarrow Fe_2O_3 + 3S$
2. Methane Flaring Chemistry
    a. $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$



A-1: Engineering Drawing, Sealing Mechanism



A-2: Circuit Diagram

A-3: Pressure Sensor Test Setup

Data		Units	Assumptions
Methane Released/Per Day	0.39863014	Kg/well/day	
Compressor Tank Size	0.2271	Cubic Meters	60 Gallon Ingersoll-Rand Compressor
Max Tank Pressure	804.386667	PSIg	Flare at 66% of Rated PSI
Methane Gas Constant	0.5182	KJ/Kg°K	
Average Yearly Temperature PA	283.15	Kelvin	
Max Capacity of Methane stored	1.24499619	Kg	PV = mRT
Time Until Compressor is Filled	3.12318632	Days	(Max Kg CH_4 stored)/(Methane Released/Per Day)

Table 1: Duty Cycle Calculations

Data		Units	Assumptions
Methane Released/Per Day	0.39863014	Kg/well/day	
Days to fill 60 Gal. Tank	6.24	Days	
v2 Compressor Power	5.59	KW	
Time to fill 60 Gal. Tank	198	Secs	
Energy to Fill tank	1106.82	KJ	
Energy Required Per Day	266.0625	KJ/Day	1.5 SF
Controls and Sensors Energy Needs	8.64	KJ/Day	
% Sunny Days Per Year	43.80%	Sunny Days	
Energy Needs Per Year	97112.8125	KJ	1.25 SF
Solar Needs	**53.1692648**	**Watts**	

Table 2: Solar Needs Calculations