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Burn Box Case Study

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Abstract

People around the world, especially in the global south make their livelihoods by processing E-waste. This process can be long and labor-intensive including brute force, chemical reactions, and incredibly high temperatures. It is also highly dangerous to the waste processors, their families, and the surrounding community.

When E-waste wires are burned to obtain precious metals, such as copper, a black smoke containing hazardous chemicals is released into the air. This smoke includes toxic heavy metals and organohalogen compounds which bioaccumulate and cause severe health risks to communities, contaminating water, soil, and food supplies.

The goal of our project was to develop a device that would reduce these toxic emissions. Specifically, we designed a 'burn-box' and scrubber which would prevent the emission of these chemicals into the ambient air as much as possible. Some of the key design constraints that we needed to consider were available tools and materials, portability, and reproducibility. This meant that we needed to use materials reasonably found on or around the E-waste site to construct our burn boxes which we designed in conjunction with the community to assure that our design would be useful and sustainable.

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1. INTRODUCTION

Electronic Waste or E-waste is composed of obsolete electronic devices which have been discarded. The regulation of E-waste is poorly enforced, resulting in the majority of 59 million tons of E-waste generated in 2019 being illegally exported to low-income countries (Turrentine 2020). At E-waste sites, recycling practices have become a type of informal economy. Components from electronic devices are either fixed or recycled for their raw materials. This includes selling the inner copper core from wires brought in from all over the site. This study focuses on Agbogbloshie, an E-waste site in Accra, Ghana where unregulated recycling activities pose a major health threat to recyclers and their communities.

Wires are burned at E-waste sites to remove the plastic coating, which presents a significant health hazard. The burns release a thick gray ashy smoke that contains toxic heavy metals, hydrochloric acid (HCl), and halogenated organic compounds, which pollute and bioaccumulate in the waters and soils of surrounding areas. Direct exposure to these emissions occur through inhalation and ingestion, posing a significant threat to human health (Zhang et al., 2012). Many of these severe health effects are still understudied, however chromosomal abnormalities, neurotoxicity and carcinogenic effects have been observed (Liu et al., 2009; Chen et al., 2011). Amankwaa (2013) found in Ghana that 96% of participants viewed E-waste Recycling as a serious health hazard while also noting that it is an important facet of the economy.

Earlier sections of the book discussed that technology without the input of the end-users can lead to unintended consequences. If left out of the design process, communities may rely on dependency to the designer. A technology reliant on the designer is inherently short-term as it prevents communities from creating a sustainable foundation to repair and build upon a technological solution. In this case study, we collaborated and communicated with the community in Accra, Ghana to avoid this outcome. Instead, we took into consideration the specific user needs, materials, and means that were available to repair and reproduce our design. By co-designing and taking the above variables into account, we aim to not only meet the needs of the Accra community, but also build a foundation that will allow for self-sufficiency and sustainability in the long term. Our approach was different, we worked with our partners in Accra and Agbogbloshie, Ghana to codesign a functioning and tested prototype burn box equipped with a filtration system. There are many hazards associated with wire burning, because of this, the process is currently illegal. We hope that our combined effort in designing the burn box will allow for the safe burning of wires with limited emissions which will help to legalize burning and reduce strain on the community.

In the following sections, we discuss in greater detail E-waste both in the Global North and lower income countries, the history of the Agbogbloshie and issues related to the recycling of wires there. We also discuss different prior incinerator and scrubber designs to build a foundation for our design. Then, we discuss the process of co-design and how we plan to use it throughout our project. Next, through interviews, design matrices, and experiments we will begin to design the burn box that meets the needs of wire-burners while reducing the amount of pollution expelled. We will then discuss the different materials and design options with the community. This will include the physical problem, weather patterns, and social aspects which may impact our design. By designing with the community, we can make this an experience of developing self-sufficiency and sustainability. To ensure the viability of our prototype, we will conclude our research by comparing the emissions released from a burn within our prototype to the emissions released in a simulated open-air burn.

2. BACKGROUND AND LITERATURE REVIEW

Safety issues caused by inadequate E-waste disposal have origins in the 18th century ("E-Waste in Developing Countries," 2020). The Industrial Revolution began a time when machines could produce products faster than humans. Governments, however, did not establish restrictions or safety precautions at the same rate. This resulted in increased incidence of injuries, long-term health conditions, and environmental pollutants. Although 300 years have passed, the relationship between safety and E-waste remains the same.

Many higher income nations such as the United States and the EU have not made enough progress towards the safe disposal of E-waste. While they have made it illegal to dispose of electronics in landfills, they continue to export E-waste to lower income nations which do not have the resources to reject the imports ("E-Waste in Developing Countries," 2020). The United States has some regulations in place regarding the disposal of E-waste, but most of the waste is recycled in the unregulated informal sector posing new threats to safety (Perkins et al., 2014). As the amount of E-waste continues to outgrow its regulation, so does exploitation and exportation to lower income countries.

E-Waste sites are complex. They have their own infrastructures, communities, economies and histories. In the next chapter, we describe how the E-waste problem arose then how these E-waste sites came from them. Afterwards we focus on Agbogbloshie, the site that we will be working with. This context was necessary to then describe the reasoning and scope behind the wire burning process and all of the dangers accompanying it. We then present a potential basis for burn box designs and scrubbers as prior art. This chapter then concludes with a description of the co-design process; a process that is essential to generative justice and the success of our project.

2.1 Growth of E-Waste?

E-waste has become one of the fastest-growing waste streams in the world (Hamouda & Adjroudi, 2017). With the continuous advancement of technology, there is always a new product that is being heavily marketed to consumers. According to the US Bureau of Economic Analysis, "Americans spent $71 billion on telephone and communication equipment in 2017, nearly five times what they spent in 2010 even when adjusted for inflation (*The World Has an E-Waste Problem*, 2019). The issue with the rapidly growing procurement of new technologies is that when something new is bought we get rid of what is old. Experts are claiming that this will result in a dramatic increase in

E-waste (*The World Has an E-Waste Problem*, 2019). Thus, the amount of E-waste and associated health risks produced every year will also continue to increase.

2.1.1 International E-Waste Policy

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal began in 1988. The goal of the convention was to promote environmentally friendly governance over the import and export of waste with a focus primarily on lower income countries (*E-Waste Laws and Regulations | Green Groundswell*, 2013). The Basel Convention "establishes standards for the transboundary movement of hazardous waste, solid waste, and municipal incinerator ash, including notice to and written confirmation from the receiving country prior to export" (US EPA, 2015). As of 2020, 187 countries and the European Commision are parties in the Convention. The United States was a signatory for the Convention but has not yet become a party. Although the United States is not a party, the Convention still impacts the country because the treaty requires that if non-parties want to export/import waste to/from parties to the Convention then a separate agreement must be established.

2.2 E-Waste in the Global North

E-waste is one of the fastest growing forms of waste in the Global North. People are more frequently purchasing, upgrading, and discarding their electronic products (Kahhat et al., 2008). The constant demand to reach a more "modern" world has created a boom in communication technologies like computers, phones, televisions, and other household items (Orisakwe et al., 2019). Another factor that contributes to frequent upgrading is the decreasing lifespan of electronics. For example, the average lifespan of laptops has decreased from four to two years, a 50% decrease (Perkins et al., 2014). Action needs to be taken to regulate disposal and recycling of E-waste, since it is one of the fastest growing components of the Global North's Municipal Solid Waste (MSW) stream.

No federal regulations currently require E-waste recycling in the US. This has forced states to establish their own laws and regulations regarding E-waste. Some examples of state regulations are "[laws that require] manufacturers of computers, computer monitors, laptop and portable computers, and televisions to provide recycling services throughout the state at no cost" to the consumer. More specifically, "the State of California has passed a law charging consumer fees, called advanced recycling fees (ARFs), at the time products are purchased" (Kahhat et al., 2008).

While these laws do help make it easier for consumers to recycle their E-waste, the majority of the waste still ends up in developing countries. Eighty percent of the E-waste generated in the United States becomes part of the "hidden flow." This means that it is unofficially exported or dumped into landfills (Perkins et al., 2014).

In Europe, less than 40% of E-waste produced is being recycled and over half of the waste produced is large household appliances (*E-Waste in the EU*, 2020). In the European Union, recycling practices vary by country. Although illegal under the Basel Convention, rich countries, like many in the EU, still export unknown amounts of E-waste to lower-income countries (Robinson, 2009). One of the main ways that the EU is working to reduce its environmental footprint due to E-waste is by passing legislation that prevents certain chemicals, like lead, to be used in the makeup of an electronic. Additionally in March of 2020 the European Commission adopted a new circular economy action plan. Since the initial adoption more initiatives have been added to the original plan. The major aims of the action plan are to "make sustainable products the norm in the EU" while focusing primarily on sectors with the most waste-like electronics (Circular Economy Action Plan, n.d.). While plans set in place aim to reduce the amount of waste produced by the European Union, exportations of the waste are still occurring.

Exporting E-waste to developing countries is common for the Global North. Labor costs and environmental regulations for hazardous waste disposal make exporting the waste the most efficient method. E-waste can provide economic benefits to lower income countries, but they are often short-lived, as these countries often lack the "technology, facilities, and resources needed to properly recycle and dispose of E-waste." This then creates public health and environmental concerns (Perkins et al., 2014).

2.3 E-Waste in Low Income Countries

Due to unregulated exports, it is hard to tell exactly how much E-waste is exported every year. The reason that high income countries have an easy time exporting to lower income countries is that they do not have "the capacity to reject imports or to handle these materials appropriately" (US EPA, 2014). There might not be any federal regulations requiring the recycling of E-waste in the United States, but there are even fewer regulations in low-income countries making them vulnerable to the onslaught of waste from other countries. According to Perkins et al., (2014), of the 20 to 50 million tons of E-waste generated annually, it can be estimated that 75% to 80% is shipped to Africa and Asia to be "recycled." This exportation of waste ends up creating villages, economies and communities. These villages are littered with waste and exposed to health and environmental risks, but they have found a way to make their lives there ("E-Waste in Developing Countries," 2020).

E-waste recycling is a form of survival in informal urban areas of lower income countries. These sites consist of homes, restaurants, vendors, street trading, and even have their own forms of government (Orisakwe et al., 2019). Each site is different in the way that its economic and social structures are established, but some aspects, like health concerns, are the same across sites. Recyclers in Sub-Saharan Africa work to repurpose functional electronic components, and strip anything else to remove the circuit boards and wires for the metals that they contain.

A key commodity is copper. Recyclers have found that the most direct and quickest way to get the copper from inside wires is to burn the PVC coating off. While this might be an effective method, it releases highly toxic chemicals that threaten the environment and human health. During the rainy seasons, toxins from E-waste sites run off into agricultural lands, contaminating crops and farm animals which are later consumed by humans ("E-Waste in Developing Countries," 2020). Around E-waste sites, pollutants "are found at significant doses in human serum, blood, hair, placenta, breast milk, and umbilical cord blood, indicating that exposure to E-waste presents a risk for the present as well as for future generations" (Orisakwe et al., 2019). Health concerns are extremely important, but for those living on or near the site, there is a need to find a way to survive, and becoming a recycler is often the answer.

2.3.1 Agbogbloshie

Agbogbloshie, located in the outskirts of Accra, Ghana is one of the largest E-waste sites in the world. The Odaw River borders most of the E-waste site which is approximately 0.4 km^2 in area. An image of wire burning alongside the river at Agbogbloshie can be seen in Figure 1. Agbogbloshie is home to roughly 80,000 people, many of whom migrated from other parts of Ghana and surrounding countries. One of the causes for the influx of people was the Konkomba-Nanumba conflict in Northern Ghana, which saw many Ghanaians move to Old Fadama, an informal settlement near Agbogbloshie (Amankwaa, 2013). Many low-income families have continued to relocate to the Old Fadama and Agbogbloshie area due to the affordable housing and opportunities for informal jobs. With shipments of E-waste from outside countries increasing over the past ten to fifteen years, E-waste recycling in Agbogbloshie has expanded immensely into an informal economy. This economy provides benefits to not only those in Agbogbloshie, but all of Ghana through their E-waste efforts.

Figure 1. Agbogbloshie Wire Burning Site

2.3.2 Agbogbloshie's Informal Economy

To understand the role Agbogbloshie plays in the E-waste economy of Ghana, it is important to define what an informal economy is and how they arise. The International Labor Organization (ILO) defines an informal economy as a "non-structured sector that has emerged in urban centers as a result of formal sectors' inability to absorb new entrants" (ILO) (1972, 9). From this definition, it is evident that the creation of an informal E-waste economy in Ghana is based on the ineffectiveness of the formal sector. The formal waste sector in Ghana deposits only 10% of solid waste into landfills and lacks the infrastructure for glass and plastic recycling (Manhart et al. 2014). ILO later defined informal economies as "consisting of units engaged in the production of goods and/or services with the primary object of generating employment and incomes to the persons concerned" (ILO 1993, 2). Agbogbloshie's informal E-waste economy also follows this definition by providing opportunities for many workers who otherwise have little to no alternatives for jobs. The Global North refers to the Agbogbloshie's E-waste industry as informal without having a full understanding of the activities and interactions that take place. While Agbogbloshie and other informal sectors may seem foreign to the Global North, Agbogbloshie's E-waste system is far more complex than what some may believe, and it can be the best way to resolve the unemployment and waste problems in Ghana.

The informal E-waste economy in Agbogbloshie can be split into different types of professions that interact and trade with each other to create a profitable and productive system. In a film about Agbogbloshie a scrap dealer named Mohammed Seidu referred to this system saying, “We are the burners, but we have others who scout in bushes to find copper, they bring it to sell to the businesspeople, so they can bring it to our company for them to be dismantled and gether the burning copper. They bring it to us to burn.” One of the job groups collects the scrap E-waste from all around the city and then brings it back to Agbogbloshie to sell to middlemen or scrap dealers. These collectors tend to be very young as this is commonly an entry level position for many who look to join the E-waste economy. Another section of the market consists of recycling printed computer boards (PCB) and copper wires for the valuable metals (ex. copper, gold, aluminum) that can be extracted. Many of these resources require expensive or time-consuming methods to obtain the materials safely and effectively from E-waste. In Agbogbloshie, these methods are not available causing many recyclers to use less safe, but effective, methods such as burning wires in open fires to remove the plastic coatings from the copper. Refurbishers also make up the informal E-waste economy by repairing used electronics through reused E-waste parts.

With 28.5% of the Ghana population living below the poverty line (GSS, 2008), this market allows affordable access to computers and other electronics to a great number of Ghanaians. The refurbishing sector has continued to grow within all parts of Ghana with many shops employing apprentices to teach future generations about their trade. The Ghanaian government contracted shops in the informal refurbishing sector in 2009 to supply the country with laptops under the “one laptop per child initiative” (Afutu-Kotey 2010). In 2015, 25% of computers in beneficiary schools and households were repaired and refurbished in Agbogbloshie (OTENG-ABABIO et al. 2015). Another bridge from the informal E-waste market to the formal market is through scrap dealers. Scrap dealers work for urban companies out of the nearby port city Tema and are considered to be the highest position in the Agbogbloshie network (Amankwaa, 2012). The Agbogbloshie E-waste sector also includes shops that operate as middlemen between the collectors, recyclers, and scrap dealers. Agbogbloshie also houses a substantial number of non-E-waste shops that provide equipment and consumables to the E-waste workers. These trade shops tend to be female dominated and create another market for job opportunities from the E-waste economy.

Agbogbloshie’s informal E-waste market not only stimulates the Ghanian economy with job opportunities, but also provides them with wages far higher than the country’s minimum wage.

With inconsistent financial return from agriculture and a saturation of workers in other low skill fields, the E-waste economy has the ability to provide more financial stability for many workers and their families. Amankwaa (2012) surveyed E-waste workers from Agbogbloshie and found that even the lowest earning group, collectors, had a daily income more than three times greater than the national daily minimum wage (see Figure 2, Amankwaa, 2012). The E-waste market accounts for the income of up to 201,600 people (Perez 2014) and contributes US $105-268 million to the Ghanian economy (Prakash and Manhart 2010).

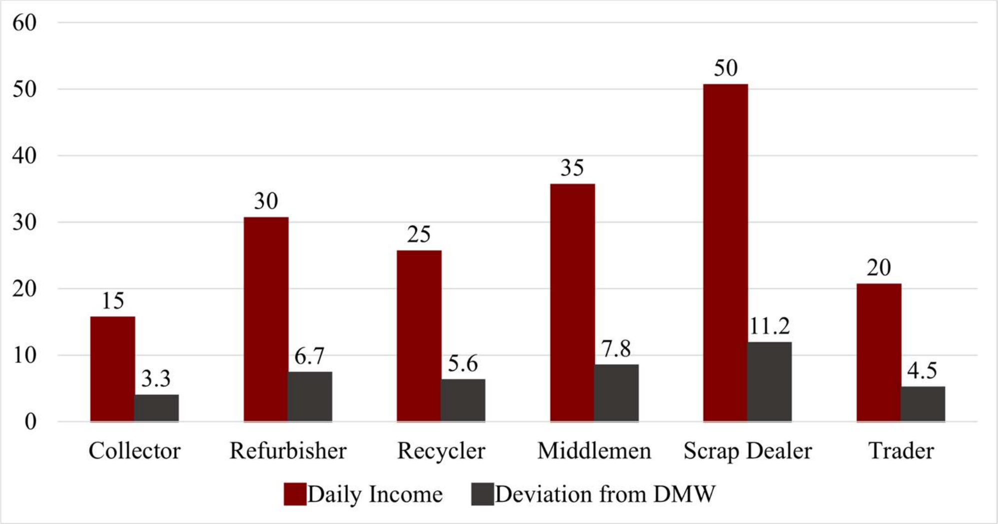


Figure 2. Daily Income Distribution of E-Waste Workers in Ghana (Amankwaa, 2012)

The Agbogbloshie's E-waste economy is therefore essential to Ghana, and, if some environmental and health issues are resolved, it can become a sustainable industry for much of Ghana's workforce.

2.4 Wire Burning

Open waste burning is prevalent throughout countries that lack the infrastructure for the proper disposal of waste. Oftentimes, to reduce the volume of waste, residential open burns and landfill burns will occur (Cogut, 2016). These burns are unregulated and often occur at low temperatures, operating at 500 °C or lower, while commercial incinerators work at temperatures of greater than 850 °C, causing unnecessary waste products to be expelled (Zhang et al., 2021). In the case of landfills, sometimes these burns are unintentional and therefore uncontrolled. All types of open burns, however, pose a great risk to communities and the planet as a whole. An example burn can be seen in Figure 3. It was predicted by the World Bank that by 2050 waste products would reach

3.4 billion tons a year (World Bank Group, 2021). Since 41% of that waste is burned annually, 1.3 billion tons of that waste will be burned, producing soil, water, and food contamination and greenhouse gas emissions (Zhang et al., 2012; Cogut, 2016).

Figure 3. Wire Burning in Agbogbloshie

Wire burning presents both economic opportunity and severe health hazards. As much of the E-waste products of the global north are exported to low-income countries, a market for the recycling and selling of these products has been created. Wires are scavenged from old electronics, burned to remove the outside coatings, and the copper is sold in this new informal economy. In Ghana this network of ‘informal employment’ represents 66.7% of all employment (Amankwaa, 2013). While this does constitute livelihoods for many people, it is not safe for the workers or their communities. The burning process unintentionally leeches harmful chemicals into the environment.

The different composition of wires impacts their burning and byproducts. Wires are either insulated or uninsulated. Insulated wires are typically composed of a copper inner core surrounded by a semiconductor and covered in a PVC sheet. Burning insulated wires produces approximately 100 times the organohalogen toxins as burning MSW (Cogut, 2016). While PVC is inherently flame retardant due to the chlorine atoms in its structure, some wires are also coated in brominated flame retardants (BFRs) (Fujimori et al., 2016; National Center for Biotechnology Information, 2022). Cables are composed of multiple types or sizes of wires, usually between 10 and 14 gauge, wrapped together including grounding and inert. These inner wires are also coated in a brominated flame retardant or paper coated in oil for insulation. These outer layers are broken down into combustion products when the wires are burned leaving behind the inner copper wire, ash, and smoke which contains organohalogens, hydrochloric acid (HCl), and toxic heavy metals.

2.4.1 Toxins and Hazards of Wire Burning

Halogenated organic compounds constitute one of the main sources of toxic emissions from wire burns. Halogenated compounds are compounds containing elements from the 7th group of the periodic table (i.e. fluorine, chlorine, bromine, iodine etc.), chlorine being an important component of PVC (National Center for Biotechnology Information, 2022). When PVC breaks down, especially at the lower temperatures constituted by the open burns, byproducts are created due to incomplete combustion (Dhoke et al., 2014; Zhang et al., 2021). It has also been found that copper acts as a catalyst when thermogenically interacting with the PVC to form halogenated compounds as well as copper complexes. These byproducts can be found in ash residue and soil samples from surrounding areas (Fujimori et al., 2016). These halogenated compounds are often found containing dangerously high amounts of chlorine and bromine from the PVC and BFRs. Some of the most common types are polychlorinated dibenzodioxins/furans (PCDD/Fs), polybrominated dibenzodioxins/furans (PBDD/Fs), and polychlorinated biphenyls (PCBs) (Cogut, 2016). Since chlorine and bromine have such similar structures, conversion will occur between the species through substitution in the burning process (Song et al., 2019). These compounds can be grouped together as dioxin related compounds (DRCs) and can be expected whenever both chlorine and bromine donors exist (Fujimori et al., 2016; Song et al., 2019).

DRCs constitute an ongoing threat to global health. PCDD/Fs constitute two of the twelve initial persistent organic pollutants (POPs) as listed at the Stockholm Convention. This was due to their ability to travel long distances, high toxicity, and ability to bioaccumulate (Song et al., 2019). While not initially listed, other DRCs have similar physicochemical properties which make them comparable or even more toxic than the PCDD/Fs (Stockholm Convention, 2019). DRCs are ubiquitous pollutants which have been detected in the soil, air, sediments, birds, marine species, fish, house dust, and human tissues surrounding waste sites (Costa & Giordano, 2007). In these areas, PCDD/Fs have been discovered in adult human tissues at 25 and 11 times the tolerable daily intake (Chan et al., 2007). This is detrimental as DRCs have negative effects on reproductive viability and can be passed through both the placental barrier and through breast milk to developing fetuses and infants (Costa & Giordano, 2007; Toms et al., 2009; Chen et al., 2011). DRCs have been shown to cause acute neurotoxicity, especially within young children, aged 2.6-3 (Toms et al., 2009). These neurotoxic effects show detriment to development of overall cognition, intelligence quotients (IQ), memory, language, gross and fine motor skills, attention, executive function, and behavior (Chen et al., 2011). While there is an apparent lack of research into the chronic effects of these chemicals on human exposure, it has been suggested that these effects may be due to a combined effect of thyroid hormone disruption and direct interference with neuronal development (Costa & Giordano, 2007). Many DRCs are also carcinogenic agents, which can damage DNA causing chromosomal aberrations and genetic mutations, increasing lifetime risk of cancer by approximately 40% (Liu et al., 2009). Their increased presence in the bloodstream is correlated with increased cases of non-Hodgkin’s lymphoma, Hodgkin’s disease, leukemia, and lung cancer (Cogut, 2016). Aside from releasing these organohalogen pollutants, the burning of E-waste also threatens human populations by releasing HCl.

The complete combustion of PVC releases HCl as corrosive and toxic vapor which dissolves in water and produces both acute and chronic effects (Cogut, 2016). There are two main classifications of toxic products released in the burning of different materials, irritants and narcotics. HCl can be classified as an irritant (Dhoke et al., 2014). The acute effects include respiratory distress caused by corrosive effects on mucous membranes and tissues. This can result in scarring and ulceration of the respiratory and digestive tracts. These chronic effects are an extension of the acute effects causing continuous degradation of the mucosal membranes (Hydrochloric acid, 2016). Eventual effects include development of glaucoma and cataracts (Cogut, 2016). So far, no carcinogenic effects have been observed due to the inhalation or ingestion of HCl. Although the toxic effects of HCl do not cause generational damage, their effects are still severe and should be prevented with the other toxins released in wire burning.

Toxic heavy metals, like HCl, cause both acute and chronic effects. The main heavy metals given off in wire burning are copper (Cu), zinc (Zn), and lead (Pb) (Gullet et, al. 2007; Cogut, 2016; Fujimori et, al. 2016). Cu and Zn are both important to supporting brain function and reaction catalysis, however when they are found in high concentrations, they can cause acute neurotoxicity. Excess copper in the brain has subsequently been linked to genetic diseases such as Alzheimer’s and Wilson’s disease, however these have not yet been studied in conjunction with the ingestion of heavy metals. Zn has been relatively more studied as it has become one of the main therapeutic targets for understanding Alzheimer's, its apparent effects include disrupting metabolism within the brain and increased Zn flux through transporters and synapses. These metals can convey their toxic effects from pregnant mothers to their fetus and therefore cause generational damage (Wright & Baccarelli, 2007). Fly ash released in the burning of E-waste, such as wires, has been found to have 200 times the acceptable Pb limits within the US (Gullet et al., 2007). Pb, unlike Cu and Zn, is not necessary for the body to function. Pb, in amounts as small as ten to twenty micrograms per dl, especially in children can have devastating effects across several organ systems such as the immune cells, kidneys, and nervous system. Together with the effects of other metals these can cause lifelong neural and physical damage (Landrigan & Todd, 1994). Toxic ash creates a somewhat unseen threat to wire burners and the surrounding community, but there are other safety concerns that also add to the dangers of this recycling process.

The process that E-waste goes through to be recycled from wires contained within expired products to copper being sold in markets is arduous and innately physical. Electrical components will fall on people's heads. Cuts, scrapes and burns are not accidents but rather part of the trade which is sustained daily (Amankwaa, 2013). Wire burners specifically are subjected to temperatures up to approximately 500°C for hours at a time, leading to dehydration and the potential for third degree burns (Zhang et al., 2021). The ash from this fire too aside from its toxicity will get into the workers eyes and lungs, drying them out. A summary of all the physical and toxic effects of wire burning can be seen in Figure 4. By designing our burn box we hope to limit both these challenges to wire burning for wire recyclers and their communities.

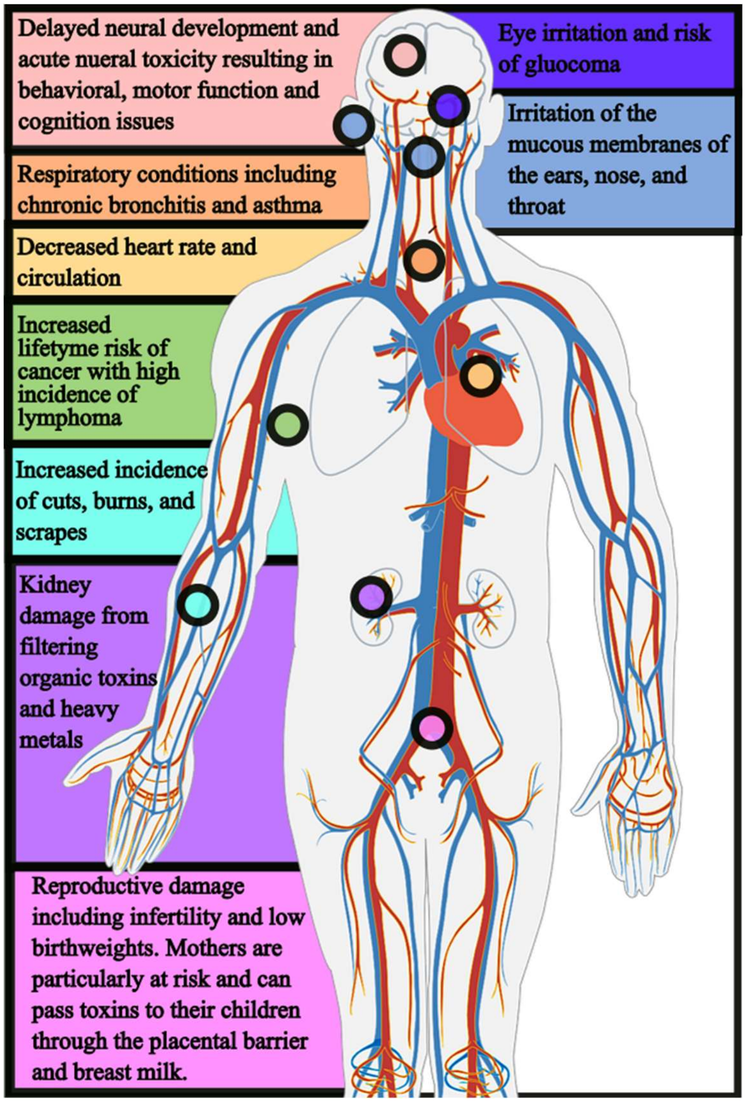


Figure 4. Effect of Wire Burning on the Human Body

2.4.2 Wire Burn Fuels

The fuels used to ignite and sustain the wire burns can also contribute to the toxicity of the wire burn process. Differing fuels cause variance in the burning temperatures obtained which can cause more toxic emissions from the wire itself (Dhoke et al., 2014; Zhang et al., 2021). Seemingly unconventional to our perspective, matches are used to light refrigerator insulation/foam and tires as fuel for these fires (Amankwaa, 2013). These fuels, however, do not allow for even distribution of heat and give off their own toxic emissions. Fuel sources frequently used in the global north are kerosine, propane, and liquified petroleum gas (LPG) which are less toxic and more easily regulated, however as we explore later, these may not be the right choice for our partners in Ghana (Brown et al., 2017).

Refrigerator insulation is often composed of polyurethane, a highly flammable compound which releases toxic gasses when burned. The emission profile from polyurethane depends on the temperature it is burned at. Lower temperatures produce more smoke and heavy organic compounds, while higher temperatures create cyanide (HCN) and carbon monoxide (CO) in much larger quantities (Singh et al., 2008). Because of the flammability of polyurethane, BFRs are also occasionally present in refrigerator insulation, however these were already taken into account with the toxicity of wire burning (Fujimori et al., 2016; National Center for Biotechnology Information, 2022). Another major concern of using any refrigeration equipment is chlorofluorocarbons (CFC's). A molecule which reacts with ozone in the atmosphere causing damage to the ozone layer (Fisher et al., 1990). This not only causes issues for our partners in Ghana but poses ongoing problems for the entire world.

Tires are already used as a fuel source in multiple processes in Ghana as a cheap, easily accessible alternative to firewood. It is even used directly to singe butchered meat. Tire burns are often executed using tires that have been cut into pieces or shredded. In both cases a significant amount of organic toxins with mutagenic/carcinogenic properties are released, three to four times the amount seen from other fuel sources (DeMarini et al., 1994). In addition to these organic toxins both irritants and narcotics are released, causing irritation to the mucous membranes and respiratory issues. Of the narcotics CO and benzene are the most notable and seen in higher concentrations when compared to the emissions of both firewood and LPG (Brown et al., 2017).

Firewood and coal are two biomass fuel sources that are currently used in Ghana. These fuels are readily available; however they are most often used as fuel sources for cooking rather than wire burns. While these fuels produce less carcinogenic effects than both tire and refrigerator insulation, they both also still produce significant amounts of irritants and narcotics such as CO and benzene, which serve to pollute the atmosphere (Brown et al., 2017).

Using a more widely accepted and easily moderated fuel source may be beneficial in our design. Gas fuels can be regulated using nozzles, which allow for a steady application of heat to be added to the furnace, while not adding other potential toxins other than those normally found in combustion reactions like CO (Brown et al., 2017). These fuel sources, however, are more expensive and there would be no way of preventing the usual fuel sources from being added to the burn box. As can be seen in Table 1, these accelerants must be taken into account when designing both the box and the filtration system.

Table 1. Wire Burning Fuel Summary

Material	Burning Temperature (°C)	Main Toxins
Wood	600	CO, benzene, nitrogen oxides, volatile organic compounds, formaldehyde, particulate matter
Charcoal	1100	CO, benzene, heavy metals, sulfur dioxide, volatile organic compounds
LPG	1900	CO, benzene
Refrigerator Insulation (Polyurethane)	800	HCN, CO, CFC's, heavy organic compounds
Tires	1100	CO, benzene, carcinogenic organic toxins

2.5 Prior Art

In this section we analyze different designs for small scale incinerators and scrubbers. Components of each design serve as a reference for what may be included or needed in the final co-designed product.

2.5.1 De Montfront University Low-Cost Medical Waste Incinerator

This incinerator design created by De Montfront University was aimed to be used in developing countries in order to dispose of medical waste. The incinerator is constructed to operate at 800 °C and to handle 15 kg/hour of waste. While this design wasn't created for E-waste, the similar parameters and affordability of the design and its materials can be a reference for other waste incinerators.

The general incinerator design consists of a loading door, chimney, air inlet, ash door, and a grate (a diagram is seen in Figure 5 and a picture of the completed design is in Figure 6). The materials used are primarily fire bricks, standard building bricks, steel tubing and sheets. This design can use both kerosene and wood as fuel for the fire.

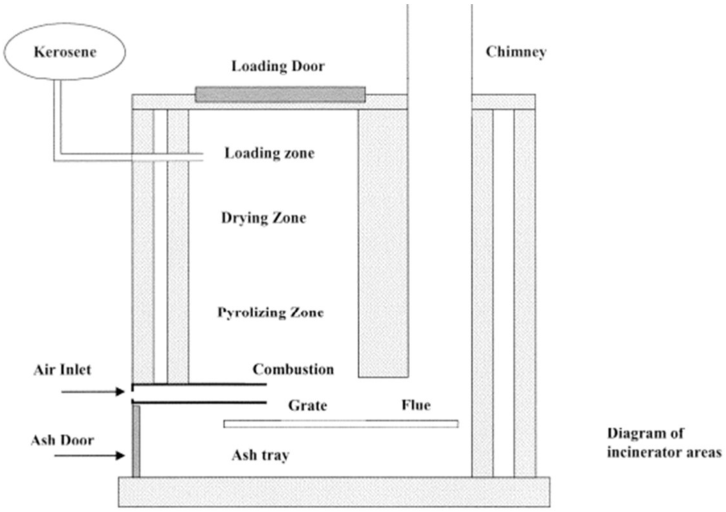


Figure 5. Incinerator Diagram

Figure 6. Incinerator Completed

2.5.2 Fluidized Bed Waste Incinerator Design

In Europe and North America, fluidized bed waste incinerators are used to dispose of waste. The incinerator system is able to separate metal for recycling and reuse the leftover ash for building materials. The steam created is utilized to create electricity by spinning a turbine. Figures 7 and 8 below show different diagrams of the fluidized bed waste incinerator to help visualize the process. In Figure 7, it shows the inputs and outputs of a fluidized bed waste incinerator. This modern design of an incinerator shows not only how far development in the technology has come but also the major features that even complex incinerators have continued to utilize over years of development.

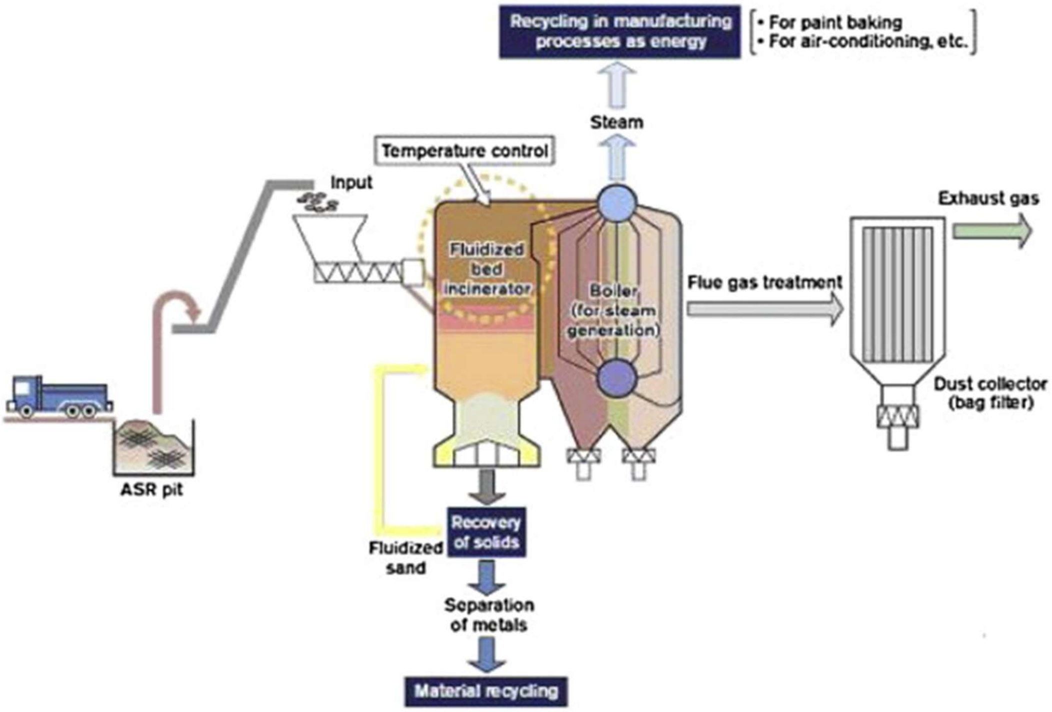


Figure 7. Fluidized Bed Waste Incinerator System

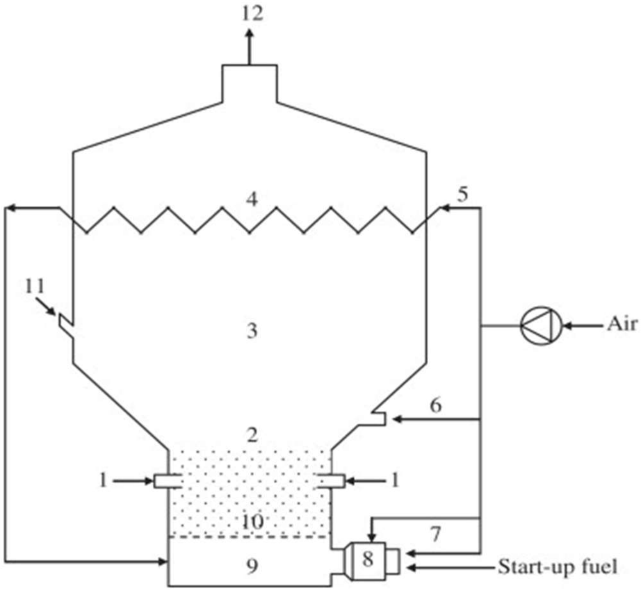


Figure 8. Fluidized Bed Waste Incinerator Diagram

2.5.3 Catalytic Converters and Reburn Tubes

Emissions from incinerators and burning stoves can be reduced by using an extended burn process. Both catalytic converters and reburn tubes are used for the burning of smoke and particulate matter given off in various combustion processes. There are two main types of catalytic converters, two-way and three-way. The three-way catalytic converter differs in that it also facilitates a reaction that allows for the reduction of nitrous oxide products (Kašpar et al., 1999). Both types use porous clay sheets impregnated with noble metals such as palladium and platinum to facilitate the complete oxidation of combustion products. An advantage of the catalytic converter is that it helps to reduce atmospheric pollutants like carbon monoxide and increase the flue temperature which allows for more stable PCDD/F formation (Pennise & Kamens, 1996). Kaivosoja (2012), however found that catalytic converters cause a significant increase in the release of PCDD/F's and Chlorophenols, both beyond the limits for MSW in the EU. This release would put extra strain on the filtration system, however, limit the hydrocarbon and particulate matter interactions. The value of noble metals needed to make the catalytic converter must also be taken into consideration as they are expensive and rare (Kaivosoja et al., 2012). Reburn tubes present a potential alternative.

Reburn tubes or secondary burn tubes use heated oxygen to facilitate the burn of smoke products. There are multiple ways to force this extra oxygen. Tubes can be added to the top of the apparatus that allow for increased air flow or a secondary air source can be added to the back of the burn allowing for air flow to occur over the initial burn. These are relatively cheap and can be executed with pipes found at the E-waste site. They result in a reduction of CO and particulate emissions the same as the catalytic converter with much less economic and manufacturing constraints.

2.5.4 Automatic Air Intake Regulators

Air intake regulators are regularly seen on wood burning stoves. These regulators can be used to regulate the fire temperature, the flue temperature, and the presence of secondary burn mechanisms. The method for air intake regulation can be as simple as a flap which raises or lowers to allow for more or less air to enter or can be as complex as Wi-Fi enabled chimney and intake controls. These are both examples of tools that could be classified as part of smart development; In our case the method which seems the simplest is the most ingenious (Nederby, 2021). In this product the ideal temperature can be set which initially moves the flap to an open position. After the chamber gets hot, the regulation occurs as a temperature dependent spring expands within the mechanism and forces the flap down over the intake valve to keep the temperature steady. As the burn chamber then begins to cool the spring contracts causing the air intake to reopen and raise the temperature.

2.5.5 Vent Pipes

Before installing a burning device, it is imperative to read about what venting pipes are necessary for the application. The type of burning that will be done in the burn box will be closest to that of a wood stove. The burning of wires can reach around 800ºC meaning the vent pipe needs to be able to handle such high temperatures, which are primarily only wood stove vents. Class A chimney pipes are used for wood stoves and are often referred to as insulated chimney pipes. The vents are either composed of double or triple walls, but double-walled pipes are most common. The inner pipe holds the emitted heat and particles from the combustion. The space between the inner and outer pipe functions as an insulator to prevent the outer pipe from reaching too high of temperatures (*Chimney and Venting Pipe Buying Guide*, 2019). While this would be a safe option for the burn box design, Class A chimney pipes are used because they run through walls and ceilings. A Class A chimney pipe would be necessary for the burn box if the burning were to be happening inside, or if it did not meet the necessary clearances from combustible materials. The burn box is going to be outside and far enough from combustible materials to allow us to use a much more cost-effective option, a stove pipe. Stove pipes are typically single walled and require an 18-inch clearance from combustible materials (Champagne 2019-01-07, n.d.). For an 8-inch diameter vent that is 48-inches long a Class A chimney pipe would be around $360 while a stove pipe of the same dimensions can be less than $70 (*Fireplaces, Stoves, Stove Pipe & Accessories*, n.d.). Stove pipes are not only more cost-efficient, but stove pipes are more commonly found than a Class A chimney pipe making it the best option when using recycled materials.

2.5.6 Scrubber Design

The toxins that do not completely combust within the incinerator portion of our design will need to be caught by the scrubber. The scrubber for the burn box will remove toxic emissions from the wire burning process. The Merriam-Webster dictionary describes a scrubber as “an apparatus for removing impurities especially from gasses.” The two main types of scrubbers are wet and dry scrubbers. Wet scrubbers use a type of liquid to dissolve the toxic fly ash from the incinerator. In our case and in many cases, this is water (Mussatti & Hemmer 2002). Dry scrubbers however use a solid matrix to capture the molecules of interest, this usually includes some form of powder. Dry scrubbers often induce some sort of chemical manipulation such as reduction agents and desulfurization (Sorrels et al., 2021). Scrubbers are often implemented in industrial processes requiring smokestacks.

Copper smelting, hospital waste and MSW burning are three processes that have similar emission profiles to those seen from wire burning sites (Song et al., 2019). Each commonly uses a filter which includes an initial screening component such as a fabric filter, a section which actively excludes certain molecules, such as an activated charcoal filter, and a final section to neutralize any molecules which get through the initial exclusion such as wet deadification.

The fuel source must also be taken into consideration when designing a filtration system. As tires and refrigerator insulation are often used for fuel in open burns, we cannot assume that these will be forgone with the implementation of our burn box (Amankwaa, 2013). Therefore, the toxins released in the burning of these fuels must also be taken into account. The main concern here will be the organic toxins and HCN released in these burns (DeMarini et al., 1994; Singh et al., 2008). The organic compounds should be captured the same as the DRC's we already accounted for, however the HCN will require special treatment. This should be neutralized through wet deadification and deacidification (Song et al., 2019).

Using Materials found in Ghana we can seek to simulate similar filtration systems. A combination of coconut husks and shells can be used to create a layered activated charcoal filter which allows for size exclusion purification of the smoke (Cobb et al., 2012). Calcination reactions using heated eggshells can be used to nullify the effects of the toxic heavy metals and acidic compounds. HCl and HCN can also be neutralized by adding a weak base/buffer to the filtration system. Life of the filter, waste disposal, and specifications will be examined as we continue in our research (Park et al., 2007).

Research, however important to the process of design, does not make up for years of experience working in and around a problem. While these prior arts are successful toward their target audience and application, our project's design must differ in its aim for use in the Agbogbloshie E-waste site. The final incinerator and scrubber was co-designed with E-waste workers and students in Ghana in order to achieve the needs and constraints involved in improving the wire burning conditions. Collaboration throughout the project will hopefully provide a long lasting, sustainable solution that can be developed and maintained independently by the Agbogbloshie E-waste workers.

2.6 Co-Design Process

When working to create a device that will benefit another community, using a co-design process helps to establish independence and self-sufficiency. To accomplish this, the design needs to begin with the community rather than the market (Telliel and Krueger). We followed a co-design process to ensure that the burn box maximizes its benefits for the end-users, the recyclers. Our team took an iterative design approach that allowed us to receive feedback on various stages of our design while working on the design directly with others in the community. We created an initial design with Academic City University College (ACUC) students and then shared that with the recyclers of Agbogbloshie to see what their thoughts were. Through each design iteration our group of Worcester Polytechnic Institute (WPI) and ACUC students were able to receive feedback and adjust accordingly. This co-design process was implemented in hopes that the burn box created would provide the community in Agbogbloshie, long term sustainability with utilizing, maintaining and developing the technology.

3. METHODS AND MATERIALS

To begin design work, we first established an understanding that contextualized the problem at hand. Our literature review allowed us to gain a surface-level understanding of the recycling and burn process. Watching documentaries created about Agbogbloshie and visiting the Wachusett Watershed Recycling Center allowed us to gain a better understanding of E-waste. After completing our research, we spoke with our co-designers to understand how they recycle E-waste at the site and to gain their input and help in designing our burn box. This section explores our design and research process. We first detail our approach towards codesign, then move towards testing and proof of concept.

3.1 Co-design with an iterative development process

Through the burn box project, we collaborated with our partners, the E-recyclers and students at Academic City University College (ACUC) in Ghana. We had conversations with both of our partners to better understand their values. Our codesign process also included weekly meetings with our student partners to review design ideas and converse about what materials and methods should be used to create the burn box.

3.1.1 Co-designing with Recyclers

We opened up discussions with wire burners in Agbogbloshie about their daily activities and the current steps involved with obtaining copper. Within these talks the health issues involved in the wire burning were discussed which allowed us to brainstorm safety precautions with our partners. Gathering information from the recyclers at Agbogbloshie gave our team insight on how to create a sustainable design. We learned about the materials available at Agbogbloshie and the size of typical wire bundles burned. This allowed us to establish material and size parameters for our design. We also learned about the typical number of burns per day, accelerants used to start the burn, ways in which the wire recyclers interact and safety issues that the recyclers face. This information was the last key piece in establishing the basis for our design.

Once our team had context for starting our designs, we were able to create preliminary designs that we could show the recyclers. We developed two main design ideas, based on the information that we received from the recyclers. Our goal with sharing our designs was to receive initial reactions, feedback, and suggestions on each design to give us an idea of the adjustments that needed to be made.

3.1.2 Co-designing with Academic City University College Students

Our team worked with three ACUC students, Louisa Ayamga, Kwabena Boateng, and Faith Cyril. The students were able to offer a different cultural perspective to the design process which was imperative in the co-designing process. We met with our partners at least once a week to go over design ideas and talk about how we can best create a burn box that allows the recyclers to keep their burning process the same while adding in key safety features. The local perspective that the students had allowed our team to see key design elements that we may have been missing or overlooking. As we began looking into building the burn box the students were also able to see what materials would be best to use based on cost and availability. By co-designing with the ACUC students our team aimed to create a burn box design that was useful and sustainable for the recyclers.

3.2 Building the Burn Box

We needed to ensure that our burn box would meet engineering standards and follow the Massachusetts burning guidelines. To address safety concerns surrounding burning on WPI's campus, we chose to use an old wood stove as proof of concept for our burn box design. The stove allowed us to safely perform burns to test all of the components in our proposed burn box namely our fire bricks and filter.

3.2.1 Preparing the Wood Stove

We went to Higgins Energy Alternatives which is a fireplace store in Barre, MA to conduct research into the operation of wood stoves and obtain used materials. Chris Higgins let us know that they take customers' old wood stoves when installing replacements. This allowed us to obtain a discarded fireplace insert wood stove to use for our project. The wood stove as donated can be seen in Figure 9A. To prepare the stove for transport we cleaned out the old ash, sanded, and added a coat of spray paint to cover the rust. This can be seen in Figure 9B. After cleaning the stove, we were able to speak with some of the workers at Higgins to decide on the best vent pipe for our use. The workers suggested using a four-foot stove pipe to allow for a strong enough draft to form. When we originally tested the stove at Higgins energy the owner, Ron Higgins suggested adding another two to four feet of pipe. In total, we added these two pipes and a chimney cap to the height of the stove. The last step to prepare the stove to be transported to our campus was to complete a small burn inside of it to ensure that the stove worked correctly. This was done outside of Higgins

Energy, and the stove was found to work with the stove pipe. Once we knew that the stove was safe to transport, it was moved to the WPI Fire Lab where we could then assemble the full structure.

A. Wood Stove Prior to Cleaning

B. Wood Stove After Cleaning

Figure 9. Donated Wood Stove from Higgins Energy

3.2.2 Creating and Testing the Fire Brick

Through the research our team conducted on prior art we learned about fire bricks. Fire bricks, also known as refractory bricks, can withstand higher temperatures than regular bricks by about 1,037°C. Regular brick can only withstand temperatures up to 482 °C which would not be enough to use for the burn box. After finding out that an individual fire brick costs upwards of $3, our team worked on finding an alternative solution. We found that you can make your own fire brick using cement, perlite, and sand. In order to see if this would be something that could be used for the final design or team conducted an experiment.

3.2.2.1 Making Standard Fire Bricks

With the help of our professor, Robert Krueger, our team created a wooden form for the bricks (seen in Figure 10). The form was made of four sides with no top or bottom so that it could easily be reused before the brick fully dried. The brick form was made to create a brick that was 9 inches long, 4.5 inches wide, and 2.5 inches tall.

Figure 10. Brick Mold

Once we had our brick form, we were able to create the brick itself. Based on two recipes for fire bricks that we had found on YouTube our team created three recipe variations to try, as seen in Table 2. The two videos we based our recipes off of are *How To Make Refractory Fire Bricks For A Forge Or Foundry 2018* and *Perlite vs Vermiculite for DIY fire bricks (Comparison) 2019*. Our team calculated the volume of one brick and used that in combination with each ingredient ratio to find the amount in quarts needed for each. Once the dry ingredients were measured into a bucket, we added water while mixing until the desired consistency was reached. For consistency, we were going for "stiff cookie dough" as one of the recipes explained it (*How to Make Refractory Concrete Step by Step)*. We lined the form with plastic and then packed the mix into the form. We let the brick set while we prepared the next mixture. When the next mixture was ready, we would lift the form from the brick, line it with more plastic, and pack it with the next mixture. We repeated this for all three bricks. Once the bricks were made and released from the form we left them to dry for two days before finding that they were fully dried.

Table 2. Standard Fire Brick Experiment Variations

Ingredients	**Brick One**	**Brick Two**	**Brick Three**
Perlite	7 Parts	7 Parts	7 Parts
Portland Cement	2 Parts	4 Parts	3 Parts
Sand	2 Parts	4 Parts	3 Parts

We performed an initial test with the fire bricks to heat resistance after the bricks had completely dried, approximately seven days after creation. These bricks were then subjected to a wood-burning fire for around an hour, so they could be raised to temperatures of 500-700°C and monitored by an infrared thermometer. The bricks were then taken out of the fire and cooled.

3.2.2.2 Making Rice Husk Fire Bricks

After speaking with our student partners at ACUC, we realized that perlite is not a common material found in Ghana. To make the recipe more accessible our team looked for alternative materials. Our team found a research paper about using rice husks to make fire bricks in Nigeria (Ugheoke et al., n.d.). After speaking with the students at ACUC we found that rice husks are more accessible than perlite. Before suggesting using rice husks in the place of perlite, our team had to create our own rice husk fire bricks and test them. Similar to how our team created the standard fire bricks, we chose five recipe variations by using a combination of the research paper and our standard brick recipe. These can be seen in Table 3. When making the bricks our team used the same wooden form that we used when making standard fire bricks. We also followed the same procedure of adding water to the dry ingredients until a “stiff cookie dough” consistency was reached. The form is again lined with plastic and the mixture is put in the form to set while the subsequent mixture is prepared. The bricks dried for five days before they were heat tested.

Table 3. Rice Husk Fire Brick Experiment Variations

Ingredients	**Brick Four**	**Brick Five**	**Brick Six**	**Brick Seven**	**Brick Eight**
Rice Husks	6 Parts	7 Parts	6 Parts	5 Parts	4 Parts
Portland Cement	2 Parts	4 Parts	4 Parts	4 Parts	4 Parts
Sand	2 Parts	4 Parts	4 Parts	4 Parts	4 Parts

Our team heat tested the rice husk fire bricks the same way that we heat tested the standard fire bricks. We placed each brick in a wood fire and left it there for an hour to expose each brick to extended heating.

3.2.2.3 Impact Testing the Fire Bricks

To test the strength of the bricks our team conducted an impact test after the bricks had been heat tested. We dropped each of the eight bricks and an industry standard brick from a height of 9.5 feet. The bricks had an impact force between 4.48 Newtons and 18.87 Newtons depending on the weight of the bricks. That corresponds to a range between 1 pound-force and 4.24 pound-force. The lightest brick was Brick One which weighed 457 grams and the heaviest brick was Brick Eight which weighed 1926 grams. The heavier the brick, the greater the impact force was. We knew that this was true because of Newton's Second Law of Motion. This law "defines a force to be equal to change in momentum (mass times velocity) per change in time" (*Newton's Laws of Motion*, n.d.). This means that the force of an object is equal to its mass times its acceleration. When an object is in free fall, like it was in impact test, the acceleration of the object is equal to the acceleration due to gravity, which is 9.8 m/s^2. This tells us that only the mass of the object influenced the impact force of the brick.

A standard brick is impact tested from 1 meter above the ground, which is close to three times less than the height we tested our bricks from. Our team chose such a high height because we wanted to ensure that the bricks were stronger than average. Because our team would be recommending our partners in Ghana use these, we needed to ensure that the bricks we recommended were structurally sound.

3.3 Scrubber Development and Design

Our main goal was to build and evaluate the functionality of a filter made with materials that could be found at Agbogbloshie. Cell culture grade powdered activated charcoal was obtained from Sigma Aldrich and granulated activated charcoal derived from coconut husks was obtained from PureT USA. Calcinated eggshells were created using 15 eggshells. These were washed with deionized (DI) water then dried for a week at room temperature then ground in a mortar and pestle. This powder was then subjected to 800°C for 3 hours and left to cool. These materials were then used to create model filtration systems for testing which were scaled up for the prototype.

3.3.1 Creation of Filtration Systems

Our first prototype filter was created using a mixture of calcined eggshells and powdered activated charcoal. A barrier was created using a cotton ball and a small layer of salt inserted to the bottom of a 250 mL column. 7.114g of calcined eggshell were then added to 10.46g of finely ground activated charcoal in an erlenmeyer flask. This mixture was then added to the column. 300mL of DI water was then applied slowly to the top of the column. Pressurized air was then used to propel the leftover water through the column.

The next filtration system was made using a system which separated out the calcinated eggshells and used both granulated activated charcoal. A cotton ball was used to plug the end of the column. This plug was then followed by a 3g layer of coarsely ground calcinated eggshell was then added followed by a 3g layer of finely ground calcinated eggshell. A 6g layer of granulated activated charcoal was then added on top of the eggshell layers to complete the filtration system.

3.3.2 Tests of the Filtration System

The two filters were tested using different sized indicator molecules to determine the size range that is best filtered. The indicator molecules and their corresponding pollutant can be seen in Table 4. This table shows a direct comparison between the molecules released in the wire burning process and indicator molecules used to test the filter. All data was found using PubChem and the National Library of Medicine.

Table 4. Toxin and Indicator Molecule Comparisons

Pollutant	Molecular Mass (g/mol)	Indicator Molecule	Molecular Mass (g/mol)
polychlorinated dibenzodioxins/furans (PCDD/Fs)	Min: 218.63 Max: 459.7	methyl orange	327.33
Polybrominated dibenzodioxins/furans (PBDD/Fs)	Min: 247.09 Max: 420.88		
Polychlorinated biphenyls (PCBs)	Min: 268.72 Max: 360.9		
HCl	36.46	methanol	32.04
HCN	27.025	carbon monoxide	28.01
Cu	63.550	copper(II) nitrate	63.55*
Zn	65.400	nickel (II) chloride	58.64*
Pb	207.000	acetyl naphthalene	170.21
*The molar mass of the dissociated metal ion species was taken.			

A 5 ml sample of each indicator molecule highlighted in blue in Table 4 was added to a round bottomed flask which was then subjected to its boiling point. The gaseous molecule was run through the column until almost no sample was left. The headspace above the filter was then sampled and GC was run to determine the presence of each indicator molecule.

For the other larger molecules this same method could not be achieved as their boiling points were too high. To understand how the filter works with these molecules we used a gravimetric approach. 5mL of a 0.5 M solution of each molecule was added to the top of the column. The column was then subjected to a high pressurized air system to force the sample through the filtration system. Overall concentration of the filtrate was then ascertained using a standard curve.

3.3.3 Translation to the Prototype Filter

Based on the most successful version of filter design as tested above, the same amounts of each filtration layer were then translated to the filtration system created for the prototype. A large empty can was used as the housing to construct the prototype filtration system. Each layer was constructed by wrapping small amounts of eggshell and activated charcoal in a wire mesh.

3.4 Prototype Testing

After the components of our prototype were tested separately, we joined them together for a final proof of concept test. We first assembled the burn box components together by adding our fire bricks inside the wood stove and fitting the filter into the chimney. We then proceeded to execute a wood burn to ensure that with all of the new components the wood stove was still able to function properly. After this we proceeded to conduct a wire burn following the process, we learned from the wire burners. The full procedure we followed and associated calculations can be found in Appendix F.

4. DATA AND RESULTS

This section details the findings of our different experiments. We initially conversed with the wire burners to gain a better understanding of their wire burn process. We then began executing our own experiments, eventually creating two different design concepts. These required the development and testing of heat resistant fire brick and a filtration system. These experiments then culminated in our final project prototype which was subsequently tested.

4.1 Preliminary Conversations with our Partners in Ghana

We began with a conversation between Julian Bennett, Adam Suale, a worker at the E-waste site, and us. This gave us insight into a few materials which may be helpful in our designs. These included: computers, air conditioners, old cars, and engine parts. From there we were also able to speak with wire burners, Mohamed Awal and Godfred Abeerengya. Mohamed and Godfred, work as a team when they burn wires and were able to discuss their process with us which can be seen in Figure 11. Together they are able to process about 20 bundles of wire, earning up to 140 Cedi or 20 USD a day. This was not the life that they chose, but it is what they do in order to survive and make a living. Godfred has burn scars up his arms from working with the wires. We were asked and thanked for the work that we are doing trying to make this process safer for everyone involved.

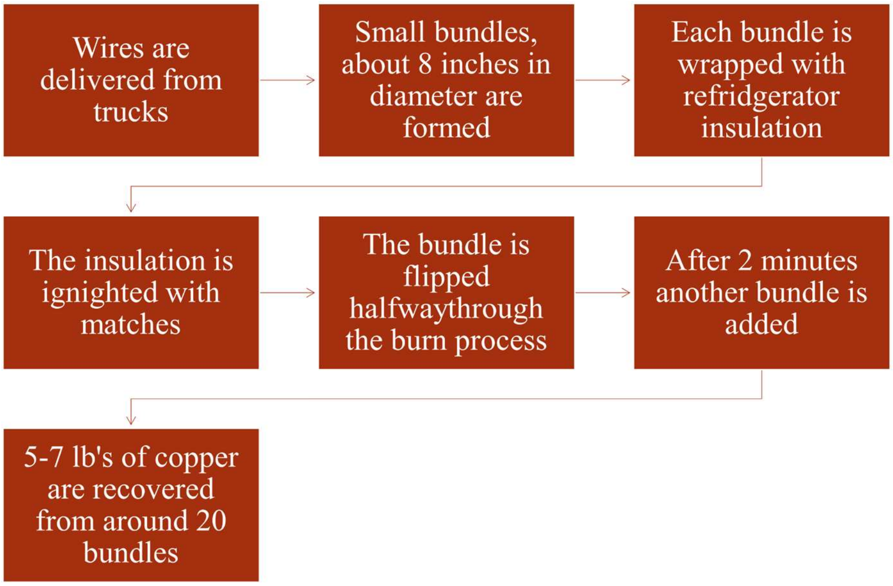


Figure 11. The Burning Process

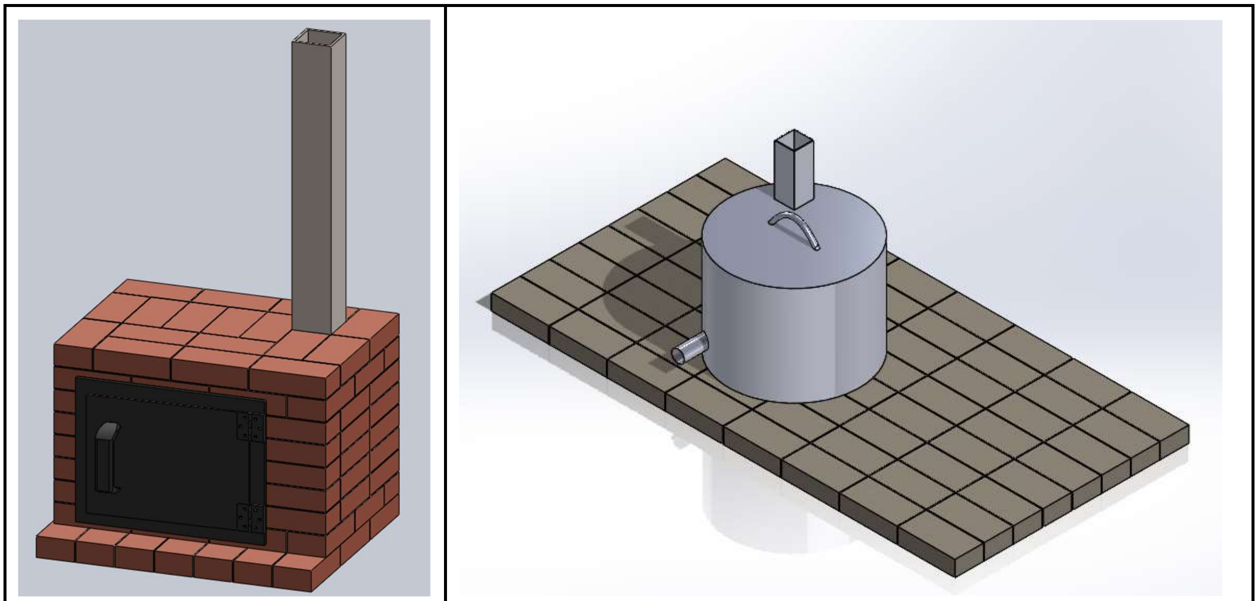
From this meeting we were able to narrow down the design components necessary for the burn box. Safety was the number one concern; we need the box to be able to insulate from both the heat and smoke. We also learned the importance of flipping the bundle of wires halfway through the burn process to allow the other side to burn. This could be due to the lack of oxygen on the underside of the bundle of wires. We could add airflow with our design, however mechanically including a component that will allow for the wires to be flipped will allow for a safer experience for the burners which does not change their current patterns. We also needed to consider the use of fuel for our design as we were told of two new fuel sources, air conditioner insulation and a liquid fuel (discussed as being petrol or kerosine) used for larger wires or when it is raining. Finally, we also learned that a box which opened as if it were an oven was desired over a top-loading box.

4.2 Burn Box Design Development

The burn box design was created and developed on Solidworks with the intention of blueprinting a detailed schematic that could be referred to in the future. The WPI student team collaborated with ACUC students to modify and add components that could improve the devices performance and are readily available in Ghana. The final Solidworks file was able to be tested through a thermal simulation in order to determine the viability and safety of the design.

4.2.1 Initial Design Ideas and Iterations

Before meeting with the ACUC students, our team brainstormed some initial designs that could be further developed into a final product. These two designs focused on overcoming the limiting parameter of the heat created through wire burning. Through our team’s background research, the material of the burn box was required to handle temperatures up to 800°C. The design in Figure 12 is mostly composed of fire brick and mortar, with only the door, air intake, and chimney being stainless steel. The design in Figure 12B consists of a 50-gallon stainless steel barrel frame with a handle, air intake, and chimney additions also made from stainless steel. This burn box design was then placed on a fire brick patio, which can allow for multiple barrels to be used on a large area patio at the same time.



A. Brick Design

B. Steel Drum Design

Figure 12. Initial Burn Box Design Ideas

Our group presented both designs to the ACUC students in our first weekly meeting. Both groups collaborated on the design iterations and researched materials and components that could be used in the burn box. We developed a burn box design that incorporated components from both the brick and steel drum designs in Figure 12. This design, shown in Figure 13, includes the same frame as the brick design but adds the steel drum on the inside of the brick, a grate, and an air intake. The steel drum was added to improve the structural strength of the brick around the frame. The grate was included to prevent a buildup of ash and past burn residue from being in contact with future wire burns which could cause a greater number of hazardous emissions to be produced.

In addition to major design changes, the ACUC students informed us that most brick molds used in Ghana are British standard size (215mm x 102.5mm x 65mm). All the bricks in the burn box design iteration, shown in Figure 13, were then changed to be British standard size to simplify the brick making process.

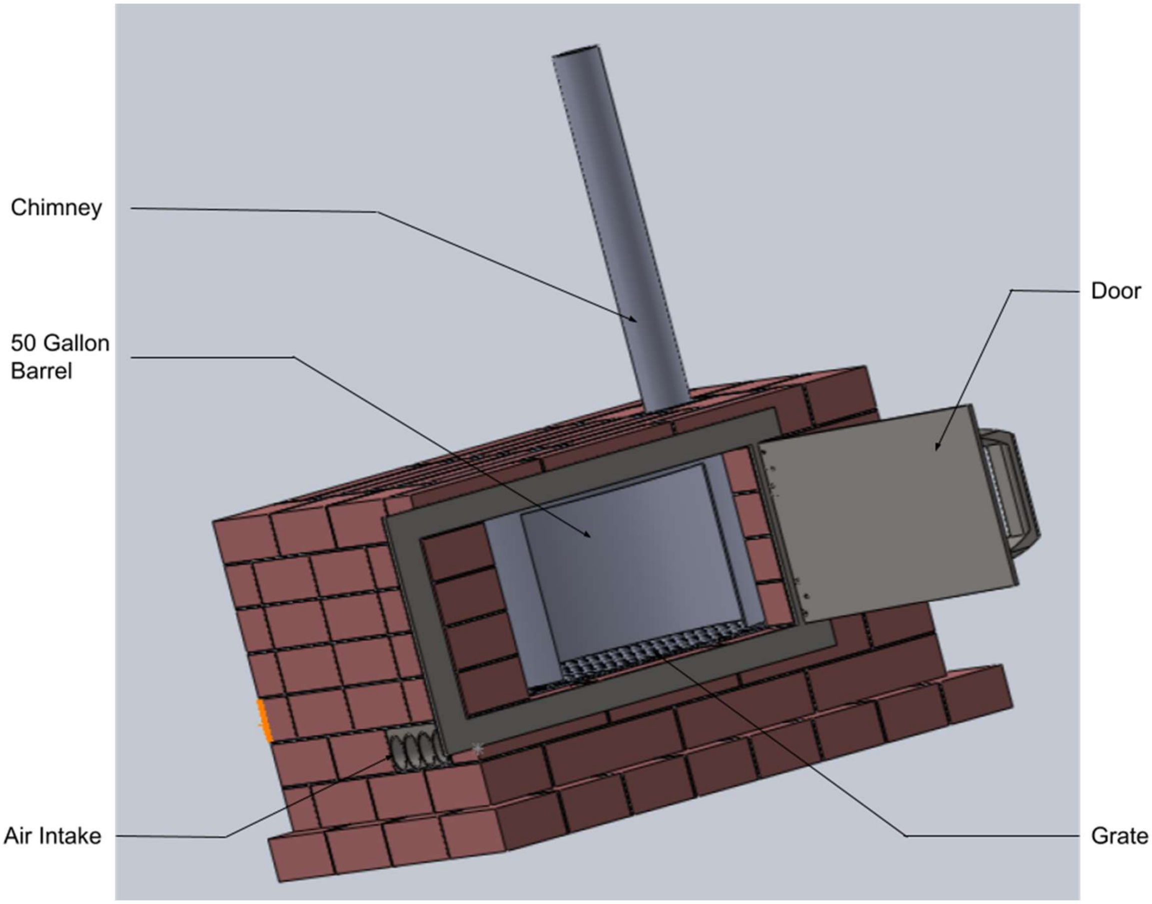


Figure 13. Burn Box Second Design Iteration

4.2.2 Final Design and Simulation

The final design for the burn box, shown in Figures 14-16, added multiple components and resizing to accomplish the device's goal. The chimney was changed to be eight feet tall with an eight-inch outer diameter and a seven and three-quarters inch inner diameter. This alteration allows for greater airflow and stack effect to handle the high amounts of smoke created from wire burning. An ashtray was added in order to safely and easily dispose of the ash and other residue created from the burning. The width of the door was increased to cover the whole front of the brick formation allowing for full access to the inner chamber. The steel drum was removed in order to make space within the burn box and was instead replaced with thin metal beams to support the brick ceiling.

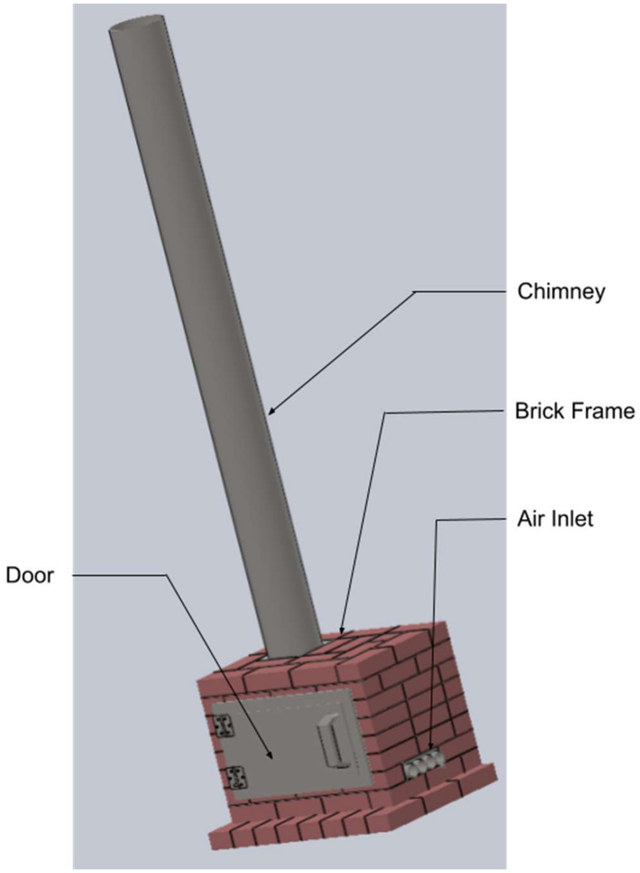


Figure 14. Completed Burn Box Design Exterior

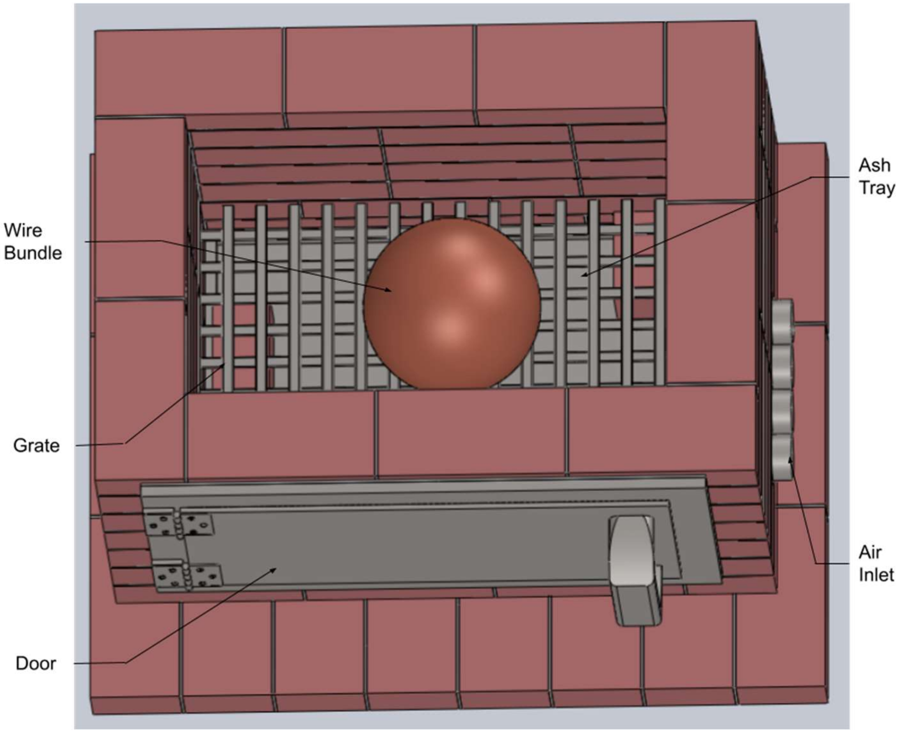


Figure 15. Completed Burn Box Design Interior Top View

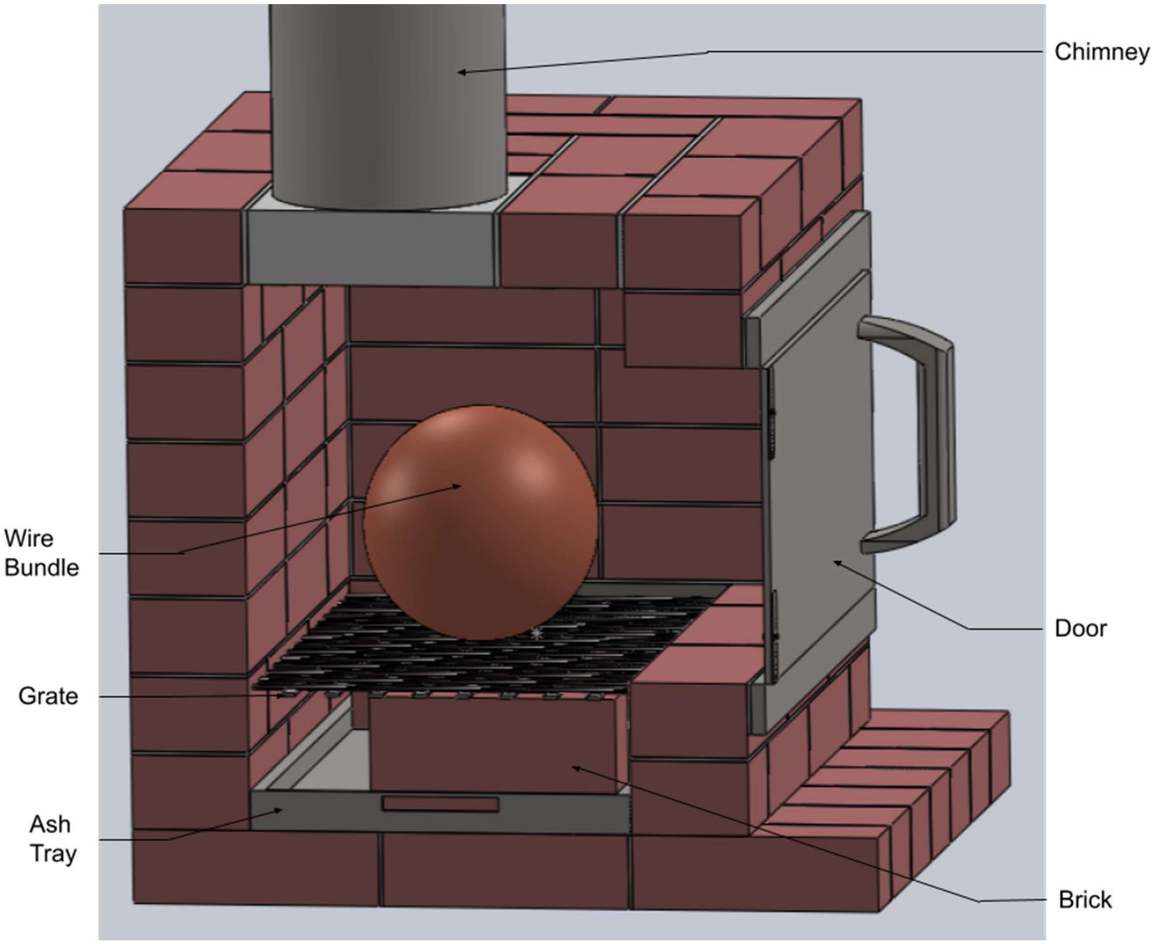


Figure 16. Completed Burn Box Design Interior Side View

Solidworks granted our team the ability to create engineering drawings and simulate thermal loads on the system, shown in Appendix E. By having the actual geometry and size of our design in Solidworks, we were able to find the temperature of different components when a thermal load is applied. The chimney, grate, and door were made of stainless steel with a thermal conductivity value preset of 37 W/(m*K). The brick and mortar were given a thermal conductivity value of 2 W/(m*K) (*Thermal Properties of Cement Mortar*, n.d.). The simulation was set up so that the 8" x 8" spherical ball on the grate, acting as a bundle of wires, was set to be 800°C. This sphere was set to 800 °C to imitate the maximum temperature of the wires during the burn. The sphere was set as copper with the preset thermal conductivity value of 390 W/(m*K). The heat from the sphere was conducted to the grate and all other components in contact. Convection values on all outside surfaces from outside air was given the temperature of 22 °C and a 25 W/(m*K) convection coefficient. Temperatures of 415 °C for the inner chimney, 100 °C for the inner brick walls, and 200 °C for the inside of the door were given from prior heat test data to evaluate the resulting outer temperatures of the burn box. The outside of the chimney temperature decreased slightly from the inside, 415 ºC to 413 ºC. The outside of the door temperature decreased from the inside, 200 ºC to 186 ºC. The outer brick wall temperature decreased from the inside, 100 ºC to 51 ºC. This thermal simulation and list of temperatures provide another approach to verify that the materials won't reach above their temperature limits and that the burn box will be safe to operate.

4.3 Fire Brick Experiment

To determine the best mixture for both the standard fire bricks and the rice husk fire bricks our team heat tested, and stress tested each brick. This allowed us to ensure that the bricks will be able to withstand the high temperatures in the burn box, as well as create a strong structure.

4.3.1 Standard Brick Heat Test Results

The three standard bricks were heated in a wood fire for one hour. The fire reached upwards of 800ºC. Each brick was then removed from the fire and given time to cool. None of the bricks appeared to have lost structural integrity during the burn.

4.3.2 Rice Husk Brick Heat Test Results

Each brick was heated in a wood fire for about an hour to see how they held up to heat. Before burning the bricks, it was visible that Brick Four seemed to be the least sturdy. Once the bricks had been in the fire for an hour, we removed them for cooling. Brick One began to break as it was removed from the fire, Brick Five had a small corner missing from it, and Brick Six, Seven, and Eight were fully intact. This followed our initial assumptions as Bricks Three, Four, and Five had the most cement and the least amount of rice husks. The last test that needed to be performed on the bricks to determine the best mixture was a stress test.

4.3.3 Impact Test for Standard and Rice Husk Bricks

Through our impact test, our team saw that some of our fire bricks could withstand a greater impact force than an industry standard fire brick. After each brick was dropped from the 9.5 feet it was inspected. Brick One, Two, Four, Five, and the Industry Standard Brick all failed. This meant that they broke into more than two pieces. Brick Three and Brick Six both had partial failures. Brick Three broke in half, but the break was clean and there was no other damage to the brick. Brick Six lost pieces from three of its corners, but the majority of the brick was still intact. Bricks Seven and Bricks Eight were the only two bricks that were dropped and had no change in their structure.

Images of the Industry Standard Brick and Bricks Three, Six, Seven, and Eight post impact test can be seen in Appendix D.

4.3.4 Overall Fire Brick Results

Throughout the tests our team was able to identify the best mixtures of both standard fire bricks and rice husk fire bricks. One of the main factors that our team identified that was imperative for having a structurally sound fire brick was the amount of cement used in the mixture. The more cement used, the better the mixture combined. Having more cement also increased the weight of the brick. To compare all the bricks that our team made, we made a table showing the visual observation of each brick, results from the heat test, and results from the impact test. Brick Two with Mortar was not impact tested because we were testing the heat capacity of the mortar as opposed to heat and strength of the brick. This can be seen in Table 5.

Table 5. Fire Brick Test Results

Brick	**Visual Observation Before Tests**	**Withstand 800 °C**	**9.5 Ft Drop Test**
Industry Standard	Fully Intact	Pass	Fail
Brick One	Fully Intact	Pass	Fail
Brick Two	Fully Intact	Pass	Fail
Brick Three	Fully Intact	Pass	Partial-Fail (broke in half)
Brick Four	Structurally Unsound (Easily Crumbled)	Fail	Fail
Brick Five	Fully Intact	Fail	Fail
Brick Six	Fully Intact	Pass	Partial-Fail (partial break)
Brick Seven	Fully Intact	Pass	Pass
Brick Eight	Fully Intact	Pass	Pass
Brick Two with Mortar	Fully Intact	Pass	Not Tested

After reviewing the results from the heat test and the impact test of the bricks our team has decided to recommend the mixture from Brick Seven (Shown in Figure 17). We chose this brick because it withstood the high heat temperatures, did not fail during the impact test, and has more rice husks than Brick Eight. Having a greater percentage of rice husks is beneficial because it is a material that we believe will be the least expensive and most available material in the mixture. Through our tests we also found that mortar made from three and a half parts sand to one part cement has the capacity to withstand the high stove temperatures without compromising its properties. Our team recommends the use of this mortar in conjunction with Brick 7 when constructing the burn box.

Figure 17. Brick 7

4.4 Filter Tests

The first filter iteration did not allow for deionized water to be passed through the activated charcoal. This meant that not only would this prevent the creation of a draft for the burn box chimney, but also did not allow for the washing of the activated charcoal which clears the pores within the charcoal granules. Due to these issues, the second filter iteration which can be seen in Figure 18 was used for testing.

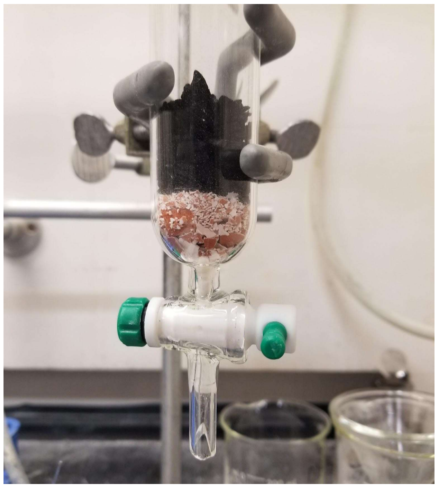


Figure 18. Filter Created for Lab Testing

The tests used to determine the filter's ability to absorb HCl and HCN, showed that these molecules would escape. The indicator molecules bubbled through the filter, methanol and carbon monoxide, were detected in the GC tests of the headspace above the filter after each test. As these toxins are similar in size to the nitrogen, oxygen, carbon dioxide, and water vapor species found in air, they needed to go through the filter, or we would not be able to create a draft. To combat this process, we added calcinated eggshells to the filter design allowing for the greater absorbance of the acidic species being released.

The larger species were found to be absorbed with differing success. Copper and zinc constituting the lower end of the molar masses that we hoped to replicate through our experiments showed that they were only absorbed to a small extent within the filter. The copper salt assay in fact resulted in an elutant that was cloudy and therefore could not be spectroscopically determined however upon visual analysis the color was slightly lighter than the original sample applied to the column. Nickel salt, which was used to simulate the size of zinc showed a 0.1M decrease after being passed through the filter. The data collected for Naphthalene and methyl orange, representing the larger polychlorinated hydrocarbon species and lead, showed that the filtrate collected had amounts of each substance that were under the limit of detection. The full data and graphs can be found in Appendix C. In Figure 19, the results of the two metal tests and the test using acetyl naphthalene can be seen. 19A shows results of the two metal tests. The first three test tubes seen from the front of the rack backwards are the standards that were tested and the fourth test tube in the row is the unknown which went through the filter. 19B shows the acetyl naphthalene filtration in progress, some of the acetyl naphthalene can be seen beaded up on the activated charcoal.

A. Metal Ion Tests

B. Acetyl Naphthalene Test

Figure 19. Filter Testing

The next step in the filter development process was to convert these findings into a filter that could be fit into our 8-inch diameter chimney. One of the main design concerns here was making sure that enough draft could get through the chimney. In order to address this, the filter was built with multiple layers, each one composed with the same bed height as tested above, however, only covering at most 50% of each layer. This filter was built with 4 layers in an old tomato can using a ¼ by ⅛ in wire mesh to support each layer composed of approximately 10 grams of activated charcoal made from coconut husks and 5 grams of calcinated eggshell. The resultant filter can be seen in Figure 20A and B showing a ¾ view a top-down view respectively.

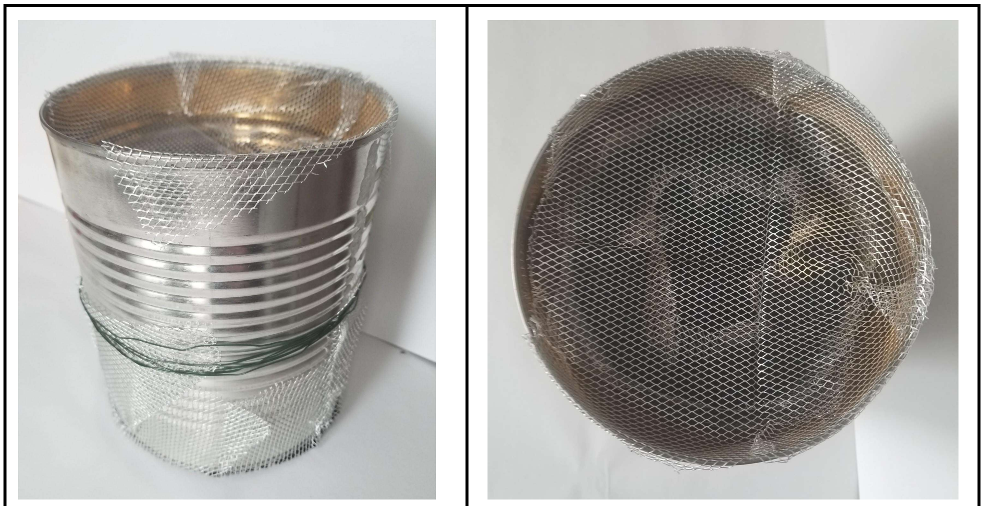

A. Side View of Filter B. Top View of Filter

Figure 20. Prototype Filter for Testing

For the creation of this product in Ghana the activated charcoal can be produced in multiple ways. The way tested above was using coconut husks to create the charcoal through a sustained burning process. This charcoal was then activated through exposure to NaCl to create pores in the charcoal, constituting a slightly less dangerous and more available means of acid activation. However, if a device is available that can maintain temperatures around 800°C for a sustained amount of time steam activation is an option which can create a more uniform pore size, but only when the high temperature is maintained. If the pore size is not properly established the filter design will not work as the molecules which need to escape through the filter may not do so as easily.

Based on the amount of activated charcoal and eggshell used to create the filter, if properly maintained, it should last 4-6 months before needing to be replaced. At the end of each week, when work is light for the wire burners, it would be ideal for both the chimney and filter to be cleaned. The chimney should be scrubbed to get rid of any built-up ash residue which can be highly flammable, and the filter should be taken out and rinsed gently or disturbed to expose the inner charcoal granules and their pores so they can absorb the molecules presented to them. The filter was fitted into the top of our design for easy removal and maintenance, so this process will require a ladder, but it should help to maintain the buoyancy of any smoke and particulate matter released.

4.5 Proof of Concept

Our final proof of concept was built out of the wood stove, a chimney cap and two chimney pipes obtained from Higgins Energy. The filter was placed within the chimney cap using a metal ring to block air flow, a wire mesh, and three screws to hold it in place. This can be seen in Figure 21C. The heat tested fire bricks were also placed in the stove as pictured in Figure 21A and B.

B. View of Fire Bricks Placed in Stove

C. Filter Inserted in the Chimney Cap

A. Full View of the Stove

Figure 21. Fully Assembled Wood Stove Burn Box

4.5.1 Final Burn Test

Our final burn test was conducted in two parts, the wood burn and the wire burn. The wood burn lasted 8.5 minutes after full ignition. The temperature data taken from both the chimney and wood stove can be seen in Figure 22. All of the smoke produced was flowing through the chimney even when the doors were opened for temperature readings in this burn indicating that we had created a strong draft.

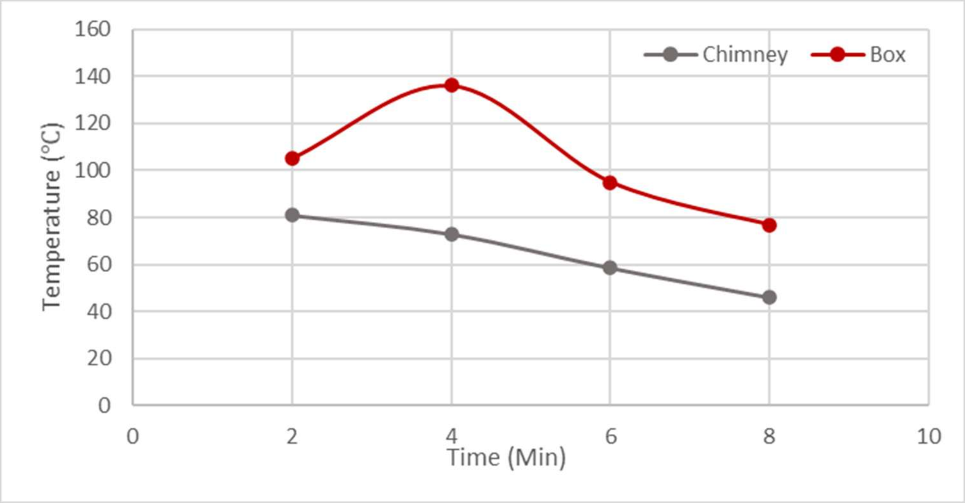


Figure 22. Final Wood Burn Temperatures

The second burn test was conducted using a bundle of wires. This bundle was created in the same fashion as described to us by the wire burners in Ghana and can be seen in Figure 24A. After ignition, chimney temperatures were recorded every minute, the graph generated can be seen in Figure 23. This test saw a small amount of smoke leaking in between the chimneys. As the fire was seen to increase after around 4 minutes the chimney temperatures slightly lagged behind. When the chimney began cooling, we saw an increase in smoke both through the top of the chimney and escaping out of the front doors. We then locked the doors to prevent more smoke from escaping. By the 10-minute mark we noticed a diminished amount of smoke and a lighter coloration indicating that the majority of the plastic had been burned. We waited until minute 24 to close the air inlet and then let the fire burn itself out.

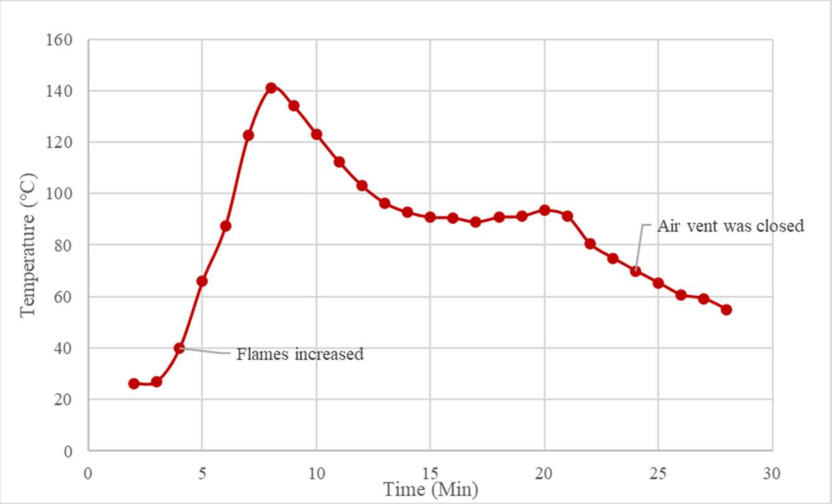
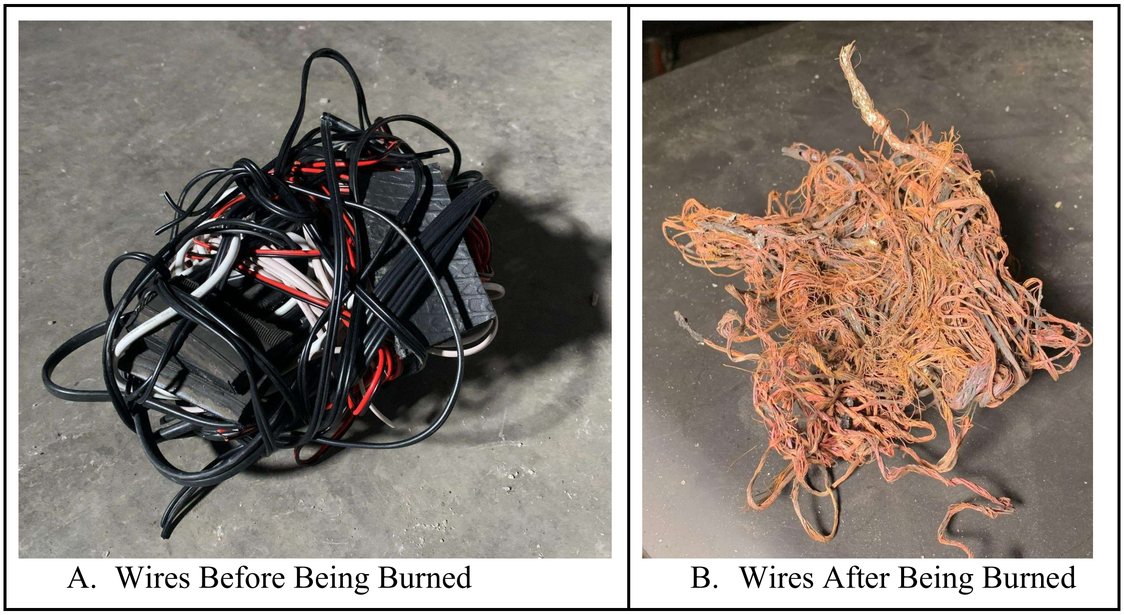


Figure 23. Wire Burn Chimney Temperatures

The day after the burn test we completed cleanup and examined the bundle of wires. While there was still a burnt plastic residue on the wires this was easily broken off by physical manipulation. The resultant wire bundle can be seen in Figure 24B.



A. Wires Before Being Burned

B. Wires After Being Burned

Figure 24. Wire Bundle Before and After Burn Test

Through our proof of concept test, our team was able to ensure that the components we tested separately would work together in our final design. Through this test we determined that our filter not only works but allows enough of a draft to be created in the chimney. We also discovered that we were reaching temperatures that were high enough to create the draft we needed and to achieve the burn results we wanted. Because of these tests we are recommending a fire brick and mortar that will be able to handle the burning process. Based on the success of this final test we believe that an unchanged wire burning process will be possible inside of a burn box implementing our design criteria.

5. DISCUSSION

Smart villages were originally built to service the global north and while the rhetoric around smart villages has changed their implementation has largely remained stagnant. Previously, smart villages have been implemented in lower-income countries as a way of control, or “white saviorism.” In our project, we sought to challenge these notions. Instead of working “for” our end-users, we were working with them. We were able to discuss different design components and processes and understand exactly what was important. Our goal, rather than to revolutionize a process that we know less about, was to learn from our partners and change as little as possible while helping to make their process safer through our designs.

Rather than relying only on our views of what science is, a lab based synthetic, neat form of inquiry we chose to look towards knowledge bases which were not the same as our own. We learned from the wire burners and the skills they had learned as a way of surviving. While they may not have measured to the thousandth place the mass of the wires they were burning and the fuel they had knowledge beyond that we could have hoped to obtain in these 8 weeks of study. We relied on their years of experience in creating and modifying our designs to something sustainable and useful. Not only that, but we were also able to better convey our ideas with our partners through these discussions.

Our strengths in design truly came from our partners and their main concerns. No matter who we were speaking with safety was the number one concern. We found that certain design aspects allowed for safer designs and were generally more desirable. We needed to work with the community to draft ideas that would work for different burners and protect those affected. Our designs therefore found their strength in those we were working with. Next time we would get in contact with the mechanical engineering students in Ghana sooner so we could have gotten more initial input before we began concretely conceptualizing our ideas. This would have allowed us to do an initial brainstorm with our partners before showing our ideas which may have limited or directed their creativity.

Generative justice can be defined in different ways. While some may reduce it to simple concepts such as value, generative justice has much more depth. In the end it is a concept of self-sufficiency in which people maintain ownership of their creations, whatever those may be. In our project we sought to promote this concept by making sure the wire burners maintained ownership over their process and how they choose to go about their work. Every design step was made with either confirmation or requests in mind from the wire burners or the ACUC students. We were not designing for the wire burners, but rather designing alongside them and that's what generative justice really meant to our team.

6. CONCLUSION

Our team was able to create a proof of concept burn box that was able to lay the foundation for a burn box being built in Ghana. While our team used an old wood stove as the structure for the burn box, we created a design model in Solidworks that we recommend being followed in Ghana. The design model includes a fire brick structure, a steel door, an 8-foot chimney with support rods and filter, and a burning platform composed of a grate and ashtray. Our team was able to create our own viable fire bricks using a mixture of cement, sand, perlite as well as a mixture of cement, sand, and rice husks. Rice husks are more commonly found in Ghana than perlite, but our team believes that in the future an attempt can be made using coconut husks in the place of rice husks. Coconut husks are the most readily available of the three potential ingredients we have listed.

6.1 Future Recommendations

While our design is a viable solution through our research and experimentation, we found several additional design options which could create a better burn box. Many of these solutions were mentioned earlier in our literature review. We would recommend that in the future these burn boxes be constructed with a form of secondary burn mechanism. These mechanisms include catalytic converters and reburn tubes. Reburn tubes especially could also benefit from a form of air intake regulation as these allow for a secondary flow of oxygen into the box. To maintain the draft needed for the chimney to be the only exit for the smoke we would need some form of air intake regulation to be added. This could be as simple as the intake regulator mentioned earlier that uses a set point and a temperature sensitive coil as a feedback mechanism. Outside of these mechanical changes we would also recommend the addition of a chimney cap. We used one for testing, however, different types being studied could be a good option for future research. Finally, we recommend subsequent design iterations continue to be designed closely with the community, and the development process to occur with the burners.

6.2 Desired Lasting Effects

Our design was created working with our partners in Ghana to fit their needs however we hope that it has a sort of universality which could be beneficial to other E-waste Sites. Since open burning of not just E-waste, but also MSW is prevalent in so many countries, our design and process could be applied as an example in these cases. Other teams can work with partners not only sharing in our designs, but also building on our use of co-design and generative justice.

Eventually through this work, we and whoever else takes up the next project will eventually create a better waste incinerator, however there will always be a better solution that we should always keep working towards.

We hope that eventually a long-term study of the effects of our burn box implementation can one day be executed. Our box, when used and functioning as expected, should promote a decrease in the observed incidence of respiratory disease, burns, and cancer in surrounding areas. For follow up studies the monitoring of soil and air pollution would be beneficial to understanding the effects of both the box and remaining pollution. We also hope that there will be other designs created within the community, by our partners or by community observers which function to create this same reduction.

Aside from the recycling activities, air pollution in Ghana is largely contributed to by the use of biomass fuels in cooking. Biomass fuels include charcoal sources such as charcoal and firewood. Emissions from these fuels are much higher than those seen in cooking with electric or LPG stoves (Afrane & Ntiamoah, 2012). There have been policies and incentives initiated in Ghana to promote the uptake of LPG stoves however this has been resisted due to monetary, safety and cooking concerns (Dalaba et al., 2018). The problem with this strategy is it was not thought of taking into account current practices and the opinions of those it was trying to help.

In designing our burn box, we developed fire brick prototypes and an almost ubiquitous filtration system. In using our product with a few changes, cook stoves could be made that allow for the safe burning of traditional fuels. This would drastically decrease air pollution and the associated negative long term health effects such as respiratory distress, cancer, and low birthweight.

6.2.1 Policy Changes in the Global North

In completing our project, we had to create a fundamental understanding of E-waste, where it goes and who it affects. The answer is that the global north is creating more E-waste than ever but not enacting the necessary policy changes to limit both this creation and its effects in downstream processing. We hope that by compiling this information through our background together with our efforts will allow a demonstration for the need for change. Manufacturing practices should be regulated such that at the end of life when and if these products end up at an E-waste site, they will not create health hazards to those working with them. These could be implemented through a decreased use of BFRs, new insulatory polymers, and better insulation. More recycling programs should also exist, assisted by manufacturers for some recycling to occur in the global north. That being said, the economy at these E-waste sites is dependent on the continued exportation of E-waste from the global north. Projects working with these sites, such as ours are important to co-design solutions to the problems this causes, however do not address the underlying issues which have created this unbalanced dependency. All we can hope to do is promote generative justice in our design practice and work to bring light to these issues.

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APPENDIX

Appendix A: Materials and Cost Analysis

Below we detail the full list of materials used in designing our prototype. These materials are also paired with their use and respective prices. The amounts used also aid in replication as we give recommendations to the amount that should be used.

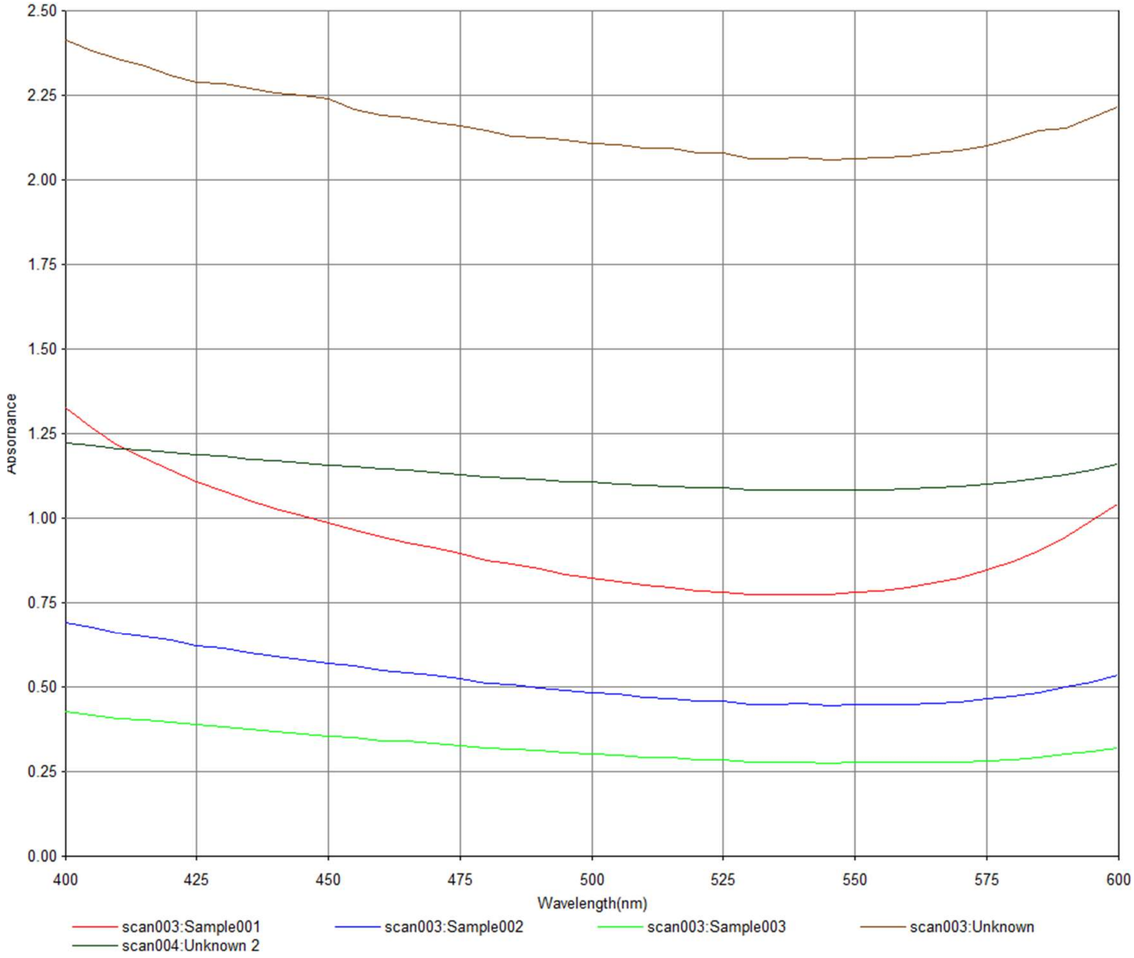
Material Costs

Use	Material	Price per ft^3*
Fire Brick	Portland Cement	\$21.29
	Sand	\$9.90
	Rice Husks	\$45.72**
	Perlite	\$8.63
Scrubber/Filter	Coconut Shell Activated Charcoal	\$46.87
	Calcinated Egg Shells	n/a**
	Metal Mesh	6.68 ft^2 **
	Large Steel-Alloy Can	n/a**

* The prices represented were found based on US pricing.
**These materials would ideally be obtained from waste products found at the site, this would mean that they could be sold by other recyclers or be found for little to no money.

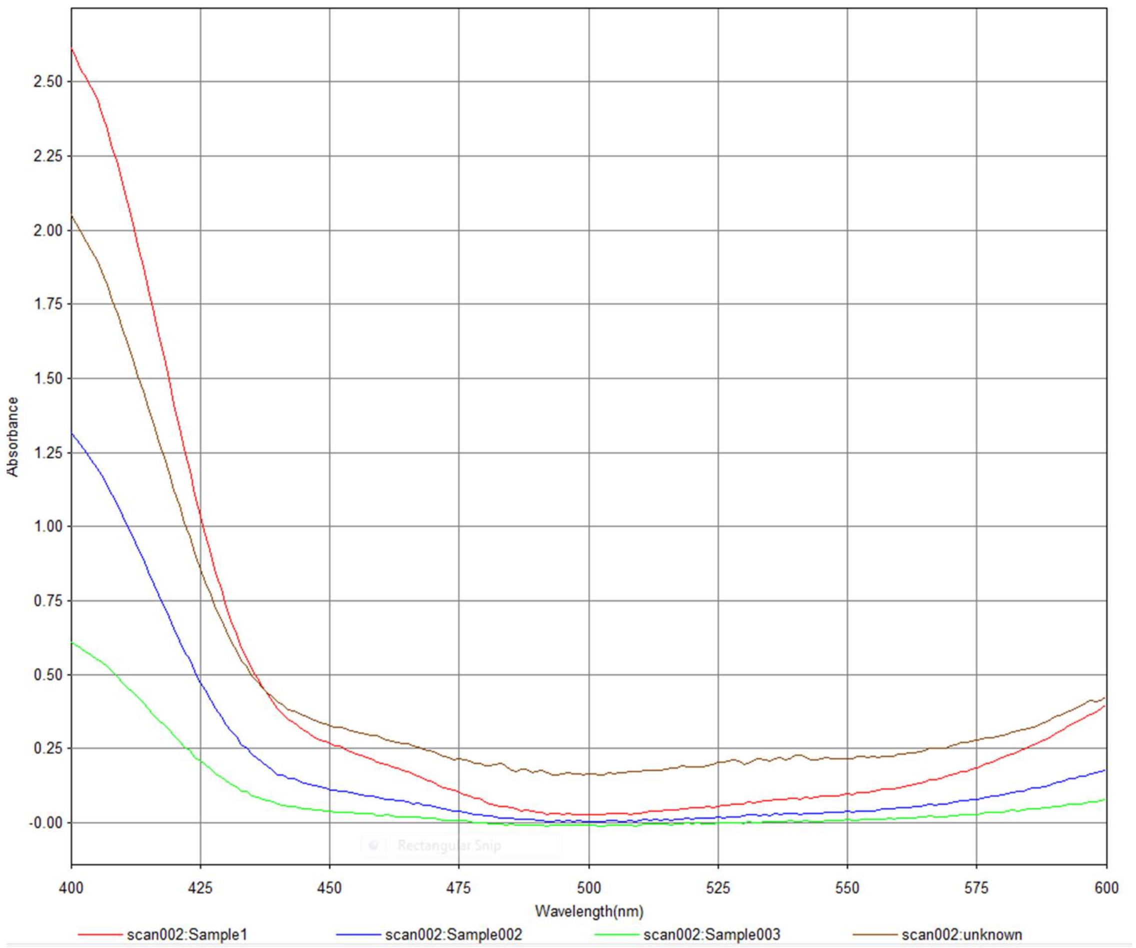
Appendix B: Filter Testing Data

This appendix details the graphs from three of the filter tests. These are discussed in the results section above however the graphs may be beneficial for added understanding.



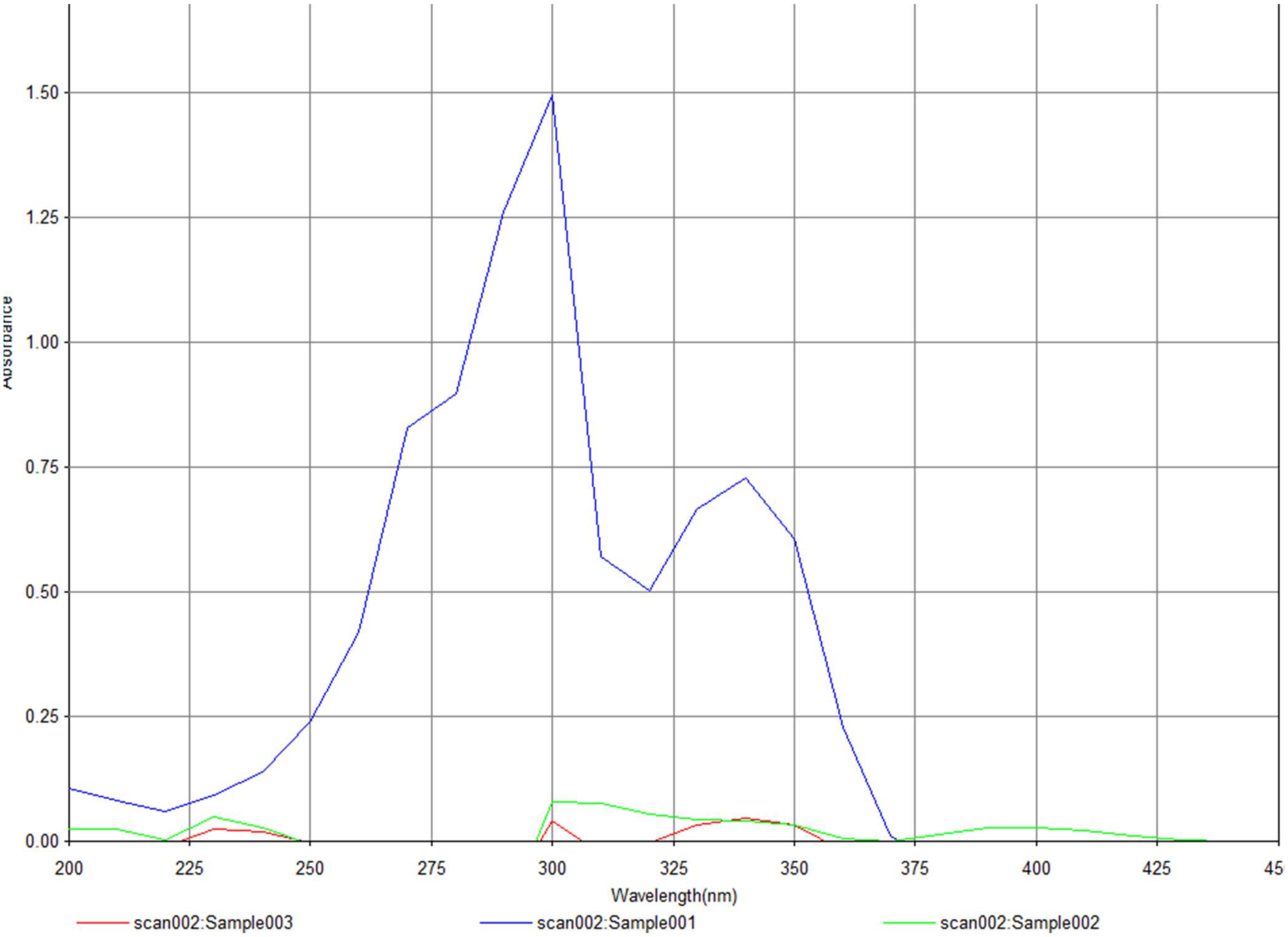
Copper (II) Nitrate Sample Absorbances

This graph shows a comparison of the absorbances recorded for samples of copper (II) nitrate. The standards tested, each a ½ dilution starting with a concentration of 0.5M can be seen in red, blue, and green. The dark green and burgundy lines above those of the standards represent the unknown which went through the filter. While these appear higher based on the absorbance data, this was due to a cloudy residue which formed during the trial. This was consistent through each trial, however the concentration of Cu in each sample could visually be processed as less as it was lighter in color.



Nickel (II) Nitrate Sample Absorbances

This graph shows a comparison of the absorbances recorded for samples of Nickel (II) nitrate. The standards tested, each a ½ dilution starting with a concentration of 0.5M can be seen in red, blue, and green. The unknown sample which went through the filter can be seen in burgundy on the graph. This contained less Ni than the 0.5M solution which was passed through the filter as it absorbs less than the 0.5M solution, however it did maintain a high concentration of Ni Ions. These results could also be confirmed by visually observing the samples as the unknown was slightly lighter in color than the highest concentration standard, but less so than the first dilution.



Acetyl Naphthalene Sample Absorbances

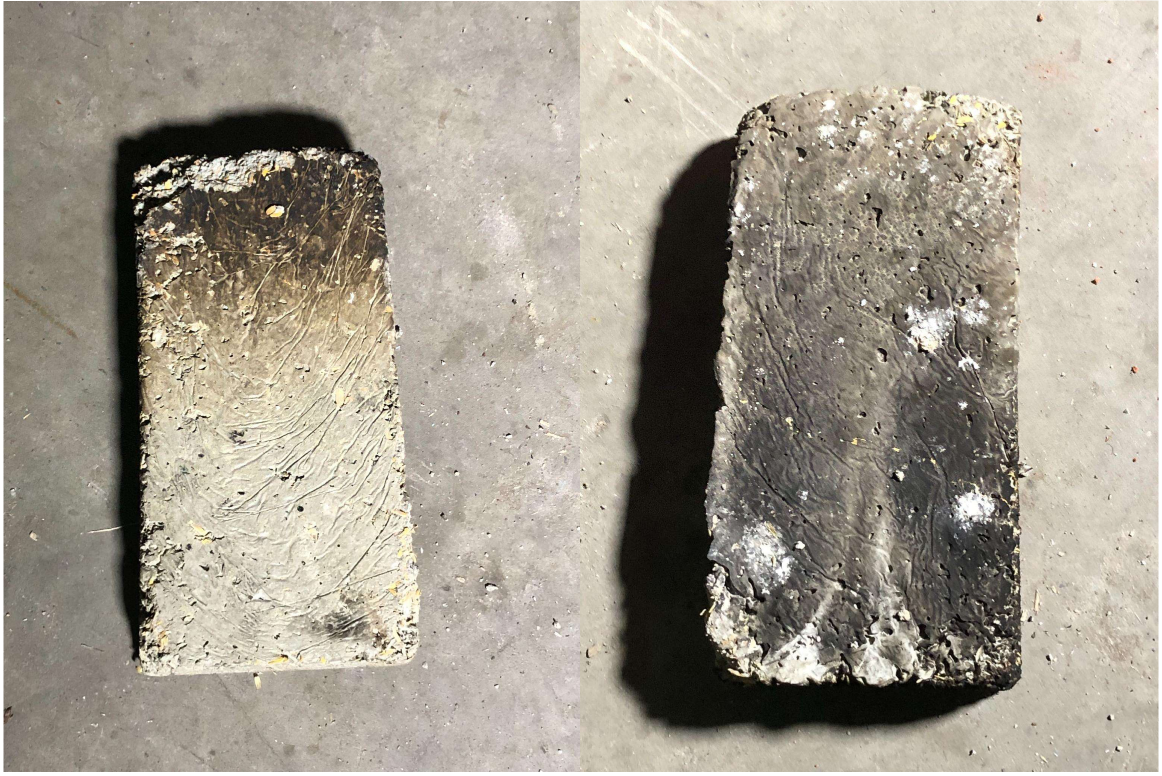
This graph shows a comparison of the absorbances recorded for samples of acetyl naphthalene. The blue line shows the absorbance profile for the standard 0.5M sample from 200-450 nm. This standard was then applied to the column and collected in two separate elutions. These elutions can be seen in green and red on the graph. As they had little to no absorbance over the entire wavelength range, there was not a significant amount of acetyl naphthalene in either of these samples. The tests using methyl orange looked largely the same however shifted to a higher wavelength range as it absorbs visible light. A graph could not be generated for methyl orange as the data was lost due to a corrupted file.

Appendix C: Perlite and Rice Husk Bricks

Brick 1 (Left) and Brick 2 (Right)

Brick 3 (Left) and Brick 4 (Right)

Brick 5 (Left) and Brick 6 (Right)



Brick 7 (Left) and Brick 8 (Right)

Brick 2 With Mortar

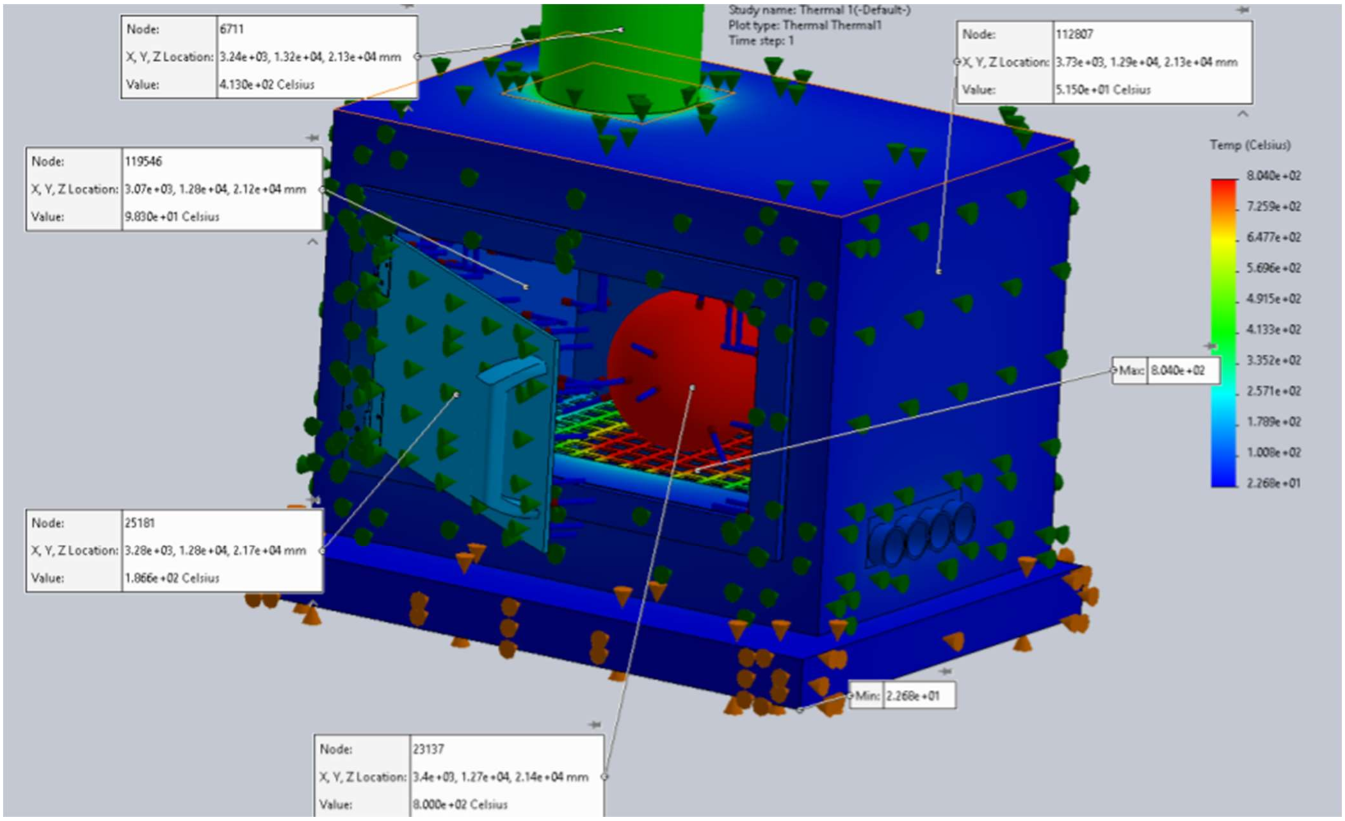
Appendix D: Impact Test Results

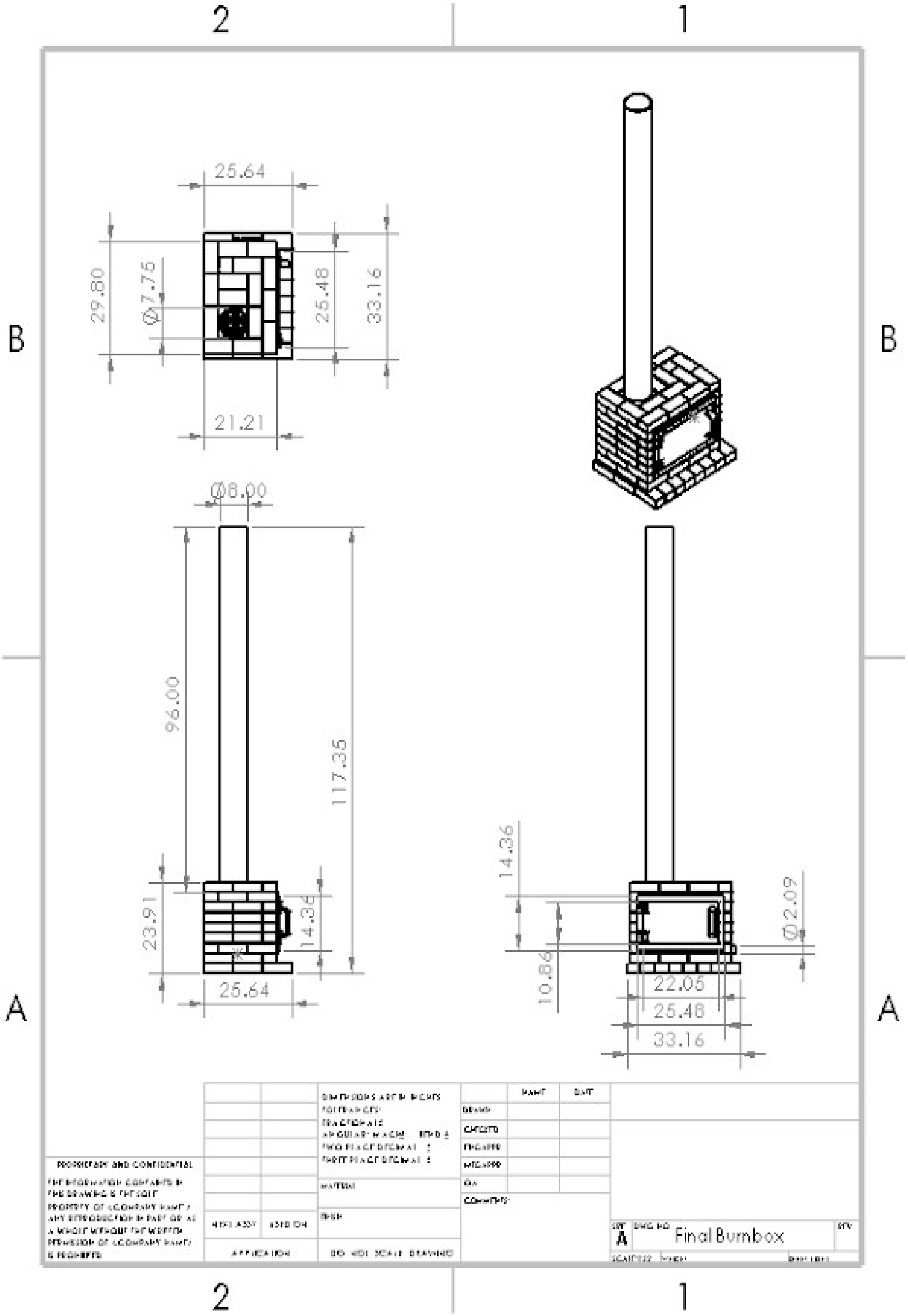
Standard Fire Brick (Left) and Brick 3 (Right)

Brick 6 (Left) and Brick 7 (Right)

Brick 8

Appendix E: Final Design Engineering Drawing and Thermal Simulation





Burn Box Engineering Drawings

Appendix F: Proof of Concept Test Plan

This appendix shows the full test plan submitted to the WPI fire lab for approval, including background, safety precautions, and procedure for the burn tests executed.

Testing the Burn Box Part 1

Objective:

To conduct qualitative initial burn test with the proof of concept burn box and chimney using wood to determine viability of a wire burn

Background:

The stove we acquired for proof of concept was an old chimney insert donated by Higgins Energy Alternatives. This stove was then retrofitted with new fire brick and an 8-foot chimney, and a filter insert. The fire brick and filter have been tested separately such that this test is to ensure that both parts work together, and a suitable draft can be created.

Cellulose, glucose polymer, is the main component of wood. The combustion of wood products can therefore be simplified to:

$$C_6H_{12}O_{6(s)} + 6O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(g)}$$

An estimated heat of combustion was calculated using an assumed 1ft log with a 5-inch diameter. This log would weigh around 3.74 kg, if dried to regular standards this means that about 20 percent of this weight is from water meaning that our log is around .7 g H2O and 3kg wood or cellulose. The adiabatic flame temperature was therefore calculated using the equation:

$$T_P = 300K + \frac{LHV \cdot N_{fuel} \cdot M_{fuel}}{\sum_i \quad N_i p\hat{c}p_i}$$

The resultant temperature was calculated to be around 580 °C. This accounts for both the amount of water stored in the log and the energy consumed in transforming that water into steam. Under non perfect conditions or non-constant pressure these are subject to change. The drier the wood the higher the resultant temperatures.

Wood burns also occur in three phases. In the first phase as documented above the fire stays around 580°C, however as the process continues and the water has converted to steam there are much higher temperatures. Instead of using the lower heating value we would be simulating the higher heating value which would result in temperatures closer to 800°C. The third stage of the fire burn includes the hot charcoal and secondary burn processes which can produce temperatures of up to 800 °C.

These calculations, however, are taking into account the absolute best conditions, in reality the heats we expect to achieve are 20-30% lower than these. Other differences we obtain may be due to the kindling used to achieve ignition temperatures, around 500°C for the wood, these however burn quickly and dissipate so were excluded for simplicity.

Materials:

1. Outdoor dried wood log/logs of approximately 4 kg or 8lbs
2. Paper and small wood scraps (kindling)
3. Standard grill lighter (source of ignition)
4. Burn box/woodstove fitted with 8ft chimney pipe and filtration device
5. Infrared thermometer
6. Sand

Safety:

Proper PPE is to be worn at all times. Katie will be wearing full PPE to light the fire within the burn box while the rest of the group will maintain a safe distance and be wearing appropriate PPE such as long pants, sleeves, and safety goggles. All persons within the vicinity will also be monitored for proper PPE and informed of the experiment in progress.

For the wood burn in case of fire outside of the burn chamber, we can use any type of fire extinguisher or water to put out the fire. If the fire expands to the chimney the choice will be to use a fire extinguisher. Chris will be in charge of the fire extinguisher during the ignition process then pass on responsibility to their partner in full PPE. Maggie will be observing both the burn box and their other two partners for any potential safety hazards and observations.

The burn box should be closely monitored for smoke exiting from any of the inlet pipes during the initial burn. This will inform the viability of further tests with PVC coated wires.

Any spectators must maintain a distance outside of the burn area underneath the hood and maintain proper PPE.

Procedure:

1. Burn box should be fully inspected, completely cleaned and ready to use by the test day in question. The fire bricks will first be added into the burn chamber. Then the filter will be added into the chimney which will be attached using a rubber mallet and screws to ensure a tight fit, which will then be reinforced with rebar.
2. The kindling (paper scraps), tinder (small wood scraps), and fuel (log) will then be arranged for ignition in the burn box. The oxygen inlet should be fully opened and the ashtray slightly open for the best airflow for ignition.
3. When ready for the burn test the burn box will be wheeled into the fume hood where Katie will ignite the kindling, with a standard grill lighter. The ash tray will then be closed completely.
4. The doors of the burn box should then be closed after ignition, every 2 minutes temperature readings will be taken at the top of the first chimney pipe and within the box using the infrared thermometer by Katie and recorded by Maggie.
5. The burn will be allowed to occur for 20 minutes or until it burns out. If the flame has not extinguished by then Katie will put out the flames using sand to smother the fire.
6. The sand and ash will then be raked through the grate and into the ash tray to prepare for the next test.

Testing the Burn Box Part 2

Objective: To conduct a qualitative wire burn test with the burn box and chimney

Background:

In this test we are trying to determine a qualitative analysis of our proof of concept, this will be through observations made as we complete a wire burn in the burn box we are using as a proof of concept.

To determine the overall heat, we expect to be produced in this burn test we had to make several assumptions. The 12-gauge wire was the average thickness for our wires used to construct the bundle. From there we were able to assume that around 75 percent of the weight of those wires was copper. If we formed a 4kg bundle, we would therefore have about 3 kg of copper to 1 kg of plastic. Assuming that all of that plastic is PVC and will be burned, we can then do a calculation to determine the heat that will be released.

If the combustion reaction were to go to completion, which occurs more frequently at higher temperatures, the resulting reaction would be:

$$[CH_3Cl] + \frac{5}{2}O_2 \rightarrow 2CO_2 + H_2O + HCl$$

Assuming this reaction goes to completion the resultant flame temperature can be calculated out to around 971℃. This however is artificially much higher than the actual value as energy is expended creating heavy organic by products such as PCDD/F's. Taking these into account the expected temperatures should be comparable to a wood fire.

What separates this even more from a wood fire, however, is the inherent fire resistance of PVC due to the included chloride group and occasional addition of a brominated flame retardant. Because of these two factors we need fuel to initially start and maintain the fire at a high enough temperature. In Ghana they will use whatever the cheapest material they can find and burn is for this goal. In our simulation we have decided to use shredded tires to simulate this. Tires are made of different types of rubber and filler material on average however they contain about 90% organic components and less than 2% water. This means if we add around 2 kg of shredded rubber to our bundle, we can expect that to contribute about 12,006 KJ of heat.

Materials:

1. Tire, shredded, about 2 kg
2. Scrap paper
3. Standard grill lighter (source of ignition)
4. 8-inch diameter wire bundle (created with the tire scraps)
5. Burn box/woodstove fitted with 8ft chimney pipe and filtration device

6. Infrared thermometer
7. ABC fire extinguisher
8. Sand

Safety:

Proper PPE is to be worn at all times. Katie will be wearing full PPE to light the fire within the burn box while the rest of the group will maintain a safe distance and be wearing appropriate PPE such as long pants, sleeves, and safety goggles. All persons within the vicinity will also be monitored for proper PPE and informed of the experiment in progress.

We have chosen to use an ABC fire extinguisher as it is meant to put out multiple fire sources including trash, liquids and electrical fires. As we are burning E-waste materials this fire extinguisher seemed the most suitable for the range of flammable items we will be burning. Just as with the wood burn, Chris will be in charge of the fire extinguisher during the ignition process then pass on responsibility to their partner in full PPE. Maggie will be observing both the burn box and their other two partners for any potential safety hazards and observations.

Any spectators must maintain a distance outside of the burn area underneath the hood and maintain proper PPE.

Procedure:

1. The 8-inch diameter bundle weighing around 6kg total between the 4 kg of wire and 2 kg of shredded tire should be constructed prior to the test day. This bundle and paper for lighting the fire should then be carefully placed in the burn box by Katie as the box will still be hot.
2. The paper should then be lit using the standard grill lighter with the ashtray slightly open and the air inlets fully open. The doors to the burn box should be shut after ensuring that the bundle is lit.
3. Temperature readings will be taken every minute at the top of the first chimney pipe using the infrared thermometer by Katie and recorded by Maggie.
4. The burn will be allowed to occur for 30 minutes, or until the flames have fully subsided. Sand will again be added to the box by Katie to ensure complete extinguination.
5. The burn box will then be removed from under the hood and the remaining ash disposed of in solid waste containers and cleaned for any other debris.