ASHRAE Applied Engineering Challenge, 2014

Improving Indoor Air Quality System

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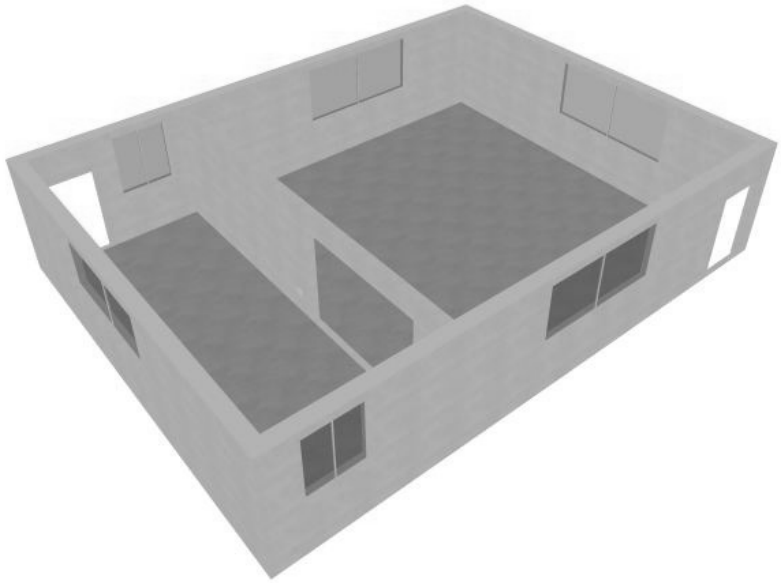
Technical Report



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Location

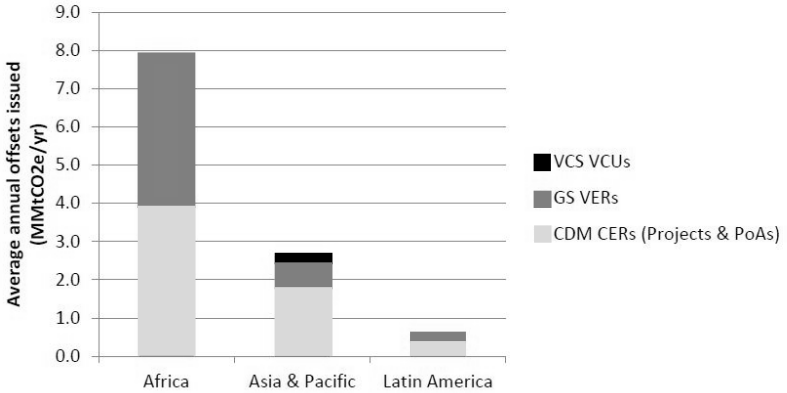
After conducting rigorous research, Mexico was chosen out of 16 other developing countries such as Argentina, Brazil, Costa Rica, and South Africa for the Applied Engineering Challenge. The location chosen for the challenge was Mexico City because of the living conditions of the natives and the improvement the presented design will provide.

Most locations within Mexico that were researched had good/fair outdoor air quality (OAQ), attributable to towns not being in or near any metropolitan areas. Mexico City is among the worst cities in the world in terms of air pollution. The air harbors multiple contaminants such as: Carbon Monoxide, Nitrogen Dioxide, Sulfur Dioxide, and Ozone [1]. These contaminants also provide justification to why Mexico City was selected - individuals can take advantage of the design to improve poor indoor air quality (IAQ) and OAQ in their home.

Figure 1: Mexico City

Mexico City is a metropolitan area where families, who live in the outskirts, tend to cook with biomass. The traditional way of cooking with biomass is the three stone cooking method; an inexpensive but also inefficient and unhealthy way of cooking because the smoke is distributed throughout the entire vicinity where it is then inhaled. Families are unaware that cooking with the three stone cooking method impacts their health negatively potentially causing health problems as severe as lung cancer. Women are particular at risk because in Mexico, women typically cook food for their families. These families also live in areas where electricity is unreliable and natural gas is unavailable. Families are left with only one viable option of cooking - the three stone method.

Figure 2 shows a chart of annual carbon offsets (projects) issued by environmental and volunteer programs, separated by region [2]. Each program has its own project, but all are based on the Kyoto Protocol's Clean Development Mechanism to reduce emissions. From the chart, Africa and Asia & Pacific regions have 2-8 projects aimed to improve IAQ, while Latin America has less than one on average annually, which gave further motivation to select Mexico City as location for this challenge.



Note: Data include both registered and validation-stage projects. CDM CERs are generated from projects using the AMS II.G and I.E methodologies. GS projects include registered and listed projects. Verified Carbon Units (VCUs) are credits issued under the Verified Carbon Standard. Sources: UNEP Risoe Centre (2012), The Gold Standard (2012), Verified Carbon Standard (2012).

Figure 2: Location of Funded Programs

Indoor/Outdoor Air Quality:

Most people believe air pollution is only related to the outdoors. However, people are more affected by the quality of air indoors than the outdoors as a result of how much time they spent inside. Having poor indoor air quality can lead to many difficulties in breathing that eventually cause asthma, allergies and other disorders [3]. There are many sources of air pollution indoors, especially in common households. In developing countries, particularly Mexico City, the main source comes from the kitchen and how food is cooked. Residents are unaware of the long term effects cooking with biomass, indoors, can have. Another major source of poor IAQ results from poor ventilation. Since most developing countries do not have strict housing and public health legislation, an affordable but effective method—such as the one presented in this report—of maintaining pollutants at low and safe concentration levels, will improve human health.

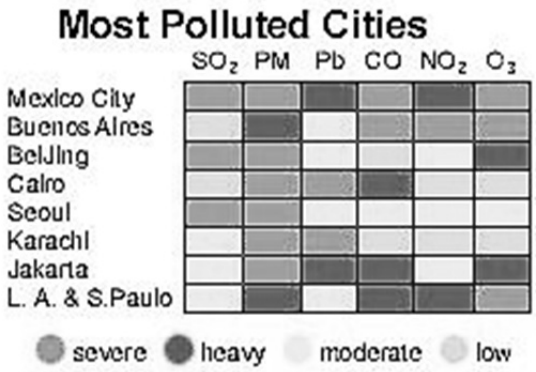


Figure 3: Top most polluted urban cities in the world.

An added challenge of improving indoor air quality in Mexico City is the poor outdoor air quality. Typically, the use of natural outdoor ventilation can improve IAQ, but the outdoor air in Mexico City is contaminated with harmful chemicals, such as the ones seen above in Figure 3. Many of the contaminants originate from the heavily dense population with over 4 million cars, 40,000 factories. Currently, governments are improving standards and mandating lower emissions to help improve OAQ in the future.

The system developed to solve the problem of outdoor and indoor air pollution involves a series of steps a family living in Mexico City can take to improve the IAQ in their house as well as informing them on the importance of keeping the air quality to healthy standards. Starting in the kitchen, the wood stove implemented will have a chimney attached to vent out the smoke caused from burning biomass. Next, in the living room, a window fan will be modified with an external air filter at the inlet of the fan, capturing most of the harmful contaminants and allowing fresh air to enter the house. With forced airflow, pollutants will be dispersed and thus avoiding high concentrations of pollutants. A window fan providing a capacity of 1400 CFM is sufficient to supply the entire house. Accounting for the pressure loss of the filter the effective air flow rate was calculated to be 1000 CFM. To prevent infiltration, caulk is to be used to seal cracks and other leaky areas, which will be further explained in the *Ventilation* section.

Weather:

In Mexico City the temperature ranges from about 37°F to 85° with an average relative humidity of 87% on hot days and 18% on cold days. Other environmental properties of Mexico City are shown in Table 1, taken from Design Builder's weather data base. Design Builder/EnergyPlus was used to model a typical house in Mexico City and the results were used to size equipment for heating, cooling, and ventilation. Design Builder was chosen as graphical user interfaces for EnergyPlus because it offers flexibility to manipulate default templates of HVAC systems and schedules to obtain realistic results.

Table 1: Mexico City's environmental properties and climate data from Design Builder

	Maximum Dry Bulb [°F]	Humidity Value [%]	Wind Speed [mph]
Summer Design Day in Mexico City	84.56	52.2	15.0
Winter Design Day in Mexico City	39.40	39.4	32.7

Standards:

Mexico follows the ASHRAE standards for mechanical systems in buildings. ASHRAE Standards 55, 62.2, & 90.2 are used to design the heating, cooling, and ventilation systems for this challenge.

Resources:

Mexico City includes businesses such as mechanical contractors and home improvement stores. There are various Home Depots in Mexico City, which is the retail store used for reference [4]. It is assumed that families have transportation capabilities, in order to purchase necessary products from Home Depot or similar stores. If the family, however, does not have any mode of transportation, Home Depot does offer delivery for an additional fee.

Family:

For this study a family of four—two parents and two children—is assumed to live in one house. A typical Mexico City family fitting this profile was researched and contacted. It was found the children attend school on weekdays, the mother works as a baker, and the father works as a construction worker; mother and father work, on average, eight to nine hours on weekdays. The average income per month of this family is about 7,100 pesos, which is equivalent to 550 US dollars [5]. Average rent for homes—on the outskirts of Mexico City ranging from 1200 ft^2 to 1500ft^2—is around 200 pesos equivalent to 150 US dollars. One of the biggest challenges is to design a heating, cooling, and ventilation systems on an affordable budget for low income families. The contacted native family from Mexico City spends about 3,250 pesos equivalent to 250 US dollars, on food. The family has, on average, savings of about 100 US dollars per month, which will help cover the cost of the design. More information regarding cost is covered in the *Cost Analysis* section.

Knowledge:

As part of the design, an informative pamphlet will be distributed to neighborhoods that are affected with the same IAQ problem. This pamphlet will have important information regarding the negative impact that bad air quality has on human health and its consequences if not resolved.
The pamphlet will have the following content:

- What are causes of poor IAQ
- Why poor IAQ is unhealthy
    - Statistics/data that researchers have conducted regarding the risk of living in a home with poor IAQ
- Ways of preventing or improving IAQ

- Outline how the design from the applied engineering challenge is one method of improving IAQ

Regardless of whether or not families can afford the design, the pamphlet could possibly serve to influence behavioral modifications and as a result people acquire a better view on health issues related to poor IAQ.

Building Envelope:

Research was done on typical homes in Mexico City to identify the materials and structures used for building envelopes. A typical home consists of concrete walls and ceiling reinforced with rebar steel. Homes around 1200 ft^2 of living area have a layout of one kitchen and one living/bed room, which is shared by all family members; bathrooms are typically located outside of the living space. Table 2 displays typical U values for the walls in addition to their dimensions and orientations.

Figure 4: Typical homes in Mexico City that met the challenge criteria

Table 2: Building envelope, U-Factors and dimensions from Design Builder

	UA Value [Btu/hr·°F]	U-Factor w/Film [Btu/hr·ft^2·°F]	Gross Area [ft^2]	Azimuth Angle [°]	Tilt Angle [°]
Living Room - South Wall	223.413	0.884	252.73	180.0	90.00
Living Room - East Wall	215.457	0.884	243.73	90.00	90.0
Living Room - West Wall	215.457	0.884	243.73	270.0	90.0
Living Room - Roof	140.668	0.185	760.37	270.0	0.00
Kitchen - North Wall	223.413	0.884	252.73	0.00	90.0
Kitchen - East Wall	87.525	0.884	99.01	90.0	90.0
Kitchen - West Wall	87.525	0.884	99.01	270.0	90.0
Kitchen - Roof	57.145	0.185	308.89	270.0	0.00

Heating Design:

The instillation of a new wood stove will provide heating during cold days, reduce pollution caused by inefficient cooking stoves, and provide reliable operation. The wood stove shown in Figure 5 is a UL certified USSC 1261 model, which can be bought at Home Depot located in Mexico City. The new stove will be located in the kitchen and it will help improve the indoor air quality by directing smoke outdoors through an exhaust duct. The wood stove is an improvement over the three stone cooking method, because it uses less biomass to produce the same of amount of heat output needed to cook. Research on the performance of an Onil stove, similar to the USSC 1261 wood stove, was compared to the performance of the typical three stone cooking method [6]. Performance figures were assigned accordingly based on the amount of time it took each stove to boil 5 liters of water, the total amount of wood used for fuel, and the amount of indoor emissions. The three stone cooking method took 26 minutes and 42 seconds to boil 5 liters of water and used 601 grams of wood with an emissions rating of 100%. The Onil stove took 28 minutes to boil 5 liters of water and used 584 grams of wood with an emissions rating of 0%. The Onil stove may have taken one minute and 18 seconds longer to boil, but it used less wood and released no indoor emission compared to the three stone cooking method. Using less wood improves the IAQ, because a decrease in wood translates to smaller fires, resulting in a decrease of smoke exposure to the inhabitants and providing a better environment for everyone. For those families that do not cook with biomass, but rather use electricity, the wood stove will solve the issue of intermittent power outages. Although electricity is the cleanest way of cooking and providing heat within a house, it is an inconvenience to families who rely on electricity if there are frequent or intermittent power outages. The USSC 1261 wood stove may not be as efficient as an electric stove, but it is more reliable. Compared to the three stone cooking method, the USSC 1261 wood stove is more efficient because cooking pots sit in designated holes on the stove top where the fire is using the heat from the fire more efficiently.

Figure 5: USSC wood stove 1261

The stove top holes are fitted with two removable lids allowing the stove to be used for heating purposes as well. The heat capacity needed to bring the home to a comfortable temperature level is about 39,000 BTU/hr. The heat output of the stove ranges from 18,000BTU/hr to 54,000BTU/hr. On cool days where the temperature can drop to 37.4°F, the kitchen is heated to a comfortable temperature of 73°F and the living room is heated to about 66°F, based on the energy modeling results. The living room is not as comfortable as the kitchen because the stove is located in the kitchen and the living room has a greater volume to be heated. To keep the family warm a few more layers of clothing can be worn, equivalent to an increase in their clothing insulation value (CLO).

Table 3: Heating and Cooling design capacities from Design Builder

	Design Size Maximum Total Cooling Capacity [Tons]	User-Specified Maximum Total Cooling Capacity [Tons]	Design Size Maximum Sensible Heating Capacity [Btu/hr]	User-Specified Maximum Sensible Heating Capacity [Btu/hr]
Living Room - Ideal Loads Air	10,440	12,000	-	-
Kitchen - Ideal Loads Air	-	-	39,022	45,998

Heating is regulated with the amount of wood that is inserted into the wood stove. The size of wood is specified in the owner's manual to get the most of every single piece of wood and in order to not overheat the stove, which shortens its life span. With proper maintenance and use, the life expectancy of a typical cast iron wood stove exceeds twenty years.

The wood stove draws in air to keep the flames burning, thus potentially bringing in unwanted air from the outside through cracks in the wall. To help reduce the infiltration of outdoor air, the stove will receive air through a dedicated supply air duct allowing outdoor air to be directed straight to the stove without bringing unconditioned air into the home. The benefit of the supply air duct is that conditioned air heated throughout the home will stay warm because no cold outdoor air will be brought in thus, bringing the temperature down. The wood stove will be using 5% less wood—saving the family money—and keep the house conditioned while providing heat at a steadier rate. The entire cost of installing the wood stove with all the necessary tools, materials, and equipment is covered in the *Cost Analysis* section.

Cooling Design:

The positive aspect of having an air conditioner is the possible reduction of humidity level, since the air in Mexico City on a hot day reaches up to 87% in relative humidity. Unfortunately, high relative humidity levels can create a perfect foundation for bacteria and mold, which can cause health problems for occupants. The IAQ of homes in Mexico City needs to be improved, and lowering the humidity level is another aspect of keeping individuals healthy and comfortable.

Figure 6: Briggs & Stratton Generator (left) and GE AEL12AR Air Conditioner (right)

The cooling system chosen for this challenge is a 115V electric wall AC unit, GE AEL12AR, shown in Figure 6. It will be located in the living room on the furthest wall from the kitchen. The air conditioning unit not only utilizes R-410A, a refrigerant which does not contribute to ozone depletion, but the unit is also an Energy Star labeled product. It provides 1 ton of cooling meeting the design capacity as presented in Table 3. This AC unit requires at most 1,111 watts of electric power to provide 1 ton of cooling and has an Energy Efficiency Ratio (EER) of 10.8. The AC unit will be plugged into a wall outlet

and when electricity is unavailable, a gasoline generator will be used to help provide electrical power to the AC unit. The gasoline generator selected is a Briggs & Stratton 030547, as shown in Figure 6, provides 3500 watts of continuous wattage power, peak wattage of 4375, and 120 volts which is enough to power the AC unit.

The generator will be located outside of the home facing its exhaust away from any windows, and as far as possible from the window fan providing the fresh air to the house. Gasoline is readily available and the generator can be used anytime when needed. Not only does the generator meet the AC unit requirements, but it also serves for emergency situations to help the community in case of an environmental disaster. The AC unit will not be used often during the year to condition the air in the living room, because Mexico City has, on average, 2 ½ hot months a year [7].

The indoor air temperature for the living room was chosen using ASHRAE Standard 55 [8], section 5.3, "Optional Method for Determining Acceptable Thermal Conditions in Naturally Conditioned Spaces". The graph depicting the acceptable operative temperature ranges for naturally conditioned spaces, shown in Figure 7, was used to determine the operative temperature. The mean monthly temperature is 77°F translating to an acceptable indoor temperature of about 84°F with natural ventilation based on the energy model results. Cooling to acceptable operative temperatures in Mexico City can be achieved without the use of an AC unit, which is why there are two tiers considered in the *Cost Analysis* section; one with the AC unit and generator, and one without.

Using the air conditioning unit on a hot day will cool the living room to 78°F and the kitchen to 84°F, which will help dehumidify the indoor air and provide a comfortable temperature for occupants. The generator will not be used often to power the AC unit, because it will be used only when the electricity from the grid is not available; the pollution from the generator exhaust gases will be minimal.

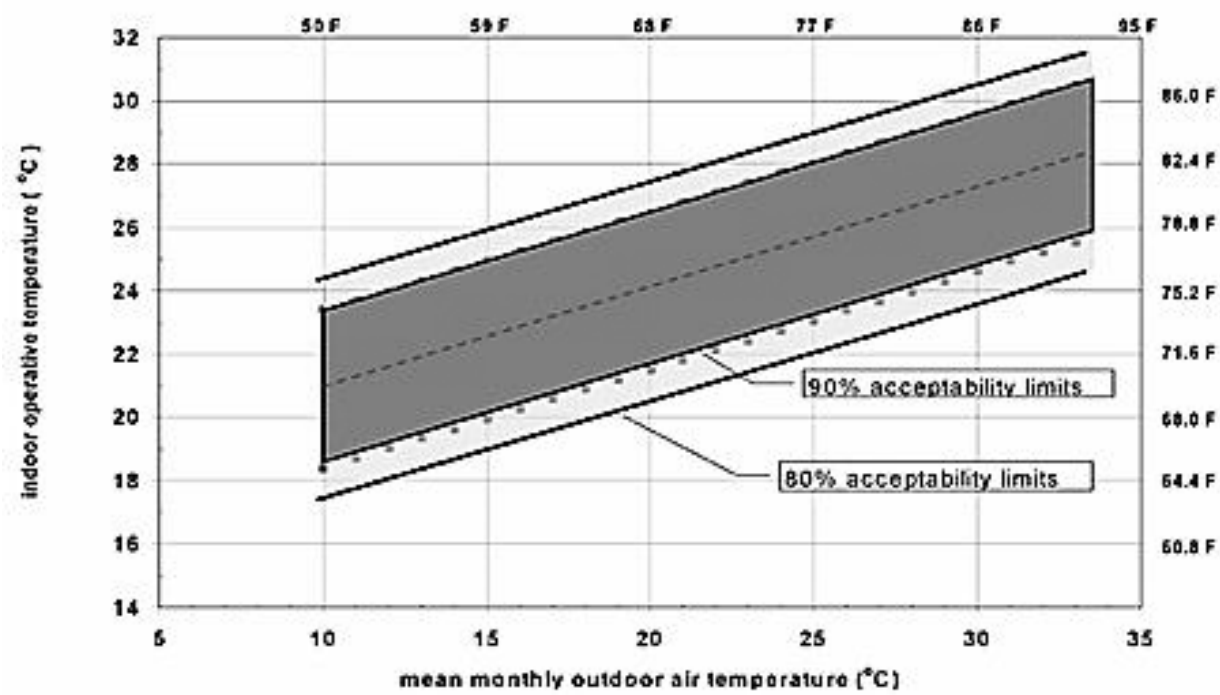


Figure 7: Adaptive Comfort, Figure 5.3 from ASHRAE 55 standards

Ventilation:

In order to help maintain and improve IAQ in any residence, proper ventilation must be established. The ventilation rates and other outside air requirements are based on ASHRAE Standard 62.2 [9]. The required minimum ventilation rate set by Standard 62.2-2013 can be calculated using Eqn.1 as stated below. Assuming a family of four and a living area of 1200 sq. ft., the minimum required ventilation rate is 66 CFM.

Eqn. 1: $$\boldsymbol{Ventilation\ Rate} = \left(\mathbf{7.5}\,\frac{\boldsymbol{CFM}}{\boldsymbol{person}}\right) + \left(\mathbf{3}\,\frac{\boldsymbol{CFM}}{\mathbf{100}\boldsymbol{ft^2}}\right)$$

Another method taken to further improve the ventilation is supersealing the house. The idea came from an ASHRAE Journal Article about the Equinox House [10], where various techniques are used to improve all aspects of the house to be more energy efficient. It was found that supersealing the house can result in saving energy, minimizing moisture movement causing mold build up, and reduced infiltration paths for insects and rodents. The plan is to seal wall-to-wall panel joints, wall-to-roof panel joints, and other building elements to reduce infiltration. A majority of homes in Mexico City are built sturdy, but allow high infiltration rates; sealing the home will reduce the amount of pollutants entering house. ASHRAE Standard 62.2 section 4 & 9, state minimum outdoor air requirements that have to be satisfied regardless of air tightness. Overall, based on the analysis conducted, it will be cost effective for the home owners in Mexico City to have homes sealed resulting in energy savings and health benefits.

To satisfy fresh air requirements, a window fan will be modified with an external air filter at the inlet of the fan, capturing most of the harmful contaminants and allowing fresh air to enter the house at a minimum rate up of 66 CFM up to 1000 CFM when natural ventilation cooling is beneficial.

The window AC unit specified in the *Cooling Design* section provides 1 ton of cooling capacity and an air recirculation rate of up to 290 CFM. The window AC unit lowers the humidity levels inside the house to provide additional protection against the build-up of mold around the house.

Portability:

The benefit of the designs presented for heating, cooling, and ventilation is that each unit is portable and can easily be installed in a new or different home. Even if the family decides to sell the home and leave everything in the home it adds value to the home. The wood stove weighs 116 pounds, which is heavy but between two people it can easily be transported or moved. The entire piping system for the wood stove can also be removed and installed in a new home. The AC unit can be taken out of the window or wall, and transported to a different home. The AC unit weighs 65 pounds, which can be carried by one person. The generator is the heaviest appliance in the home, weighing 119 pounds, but it is a lot easier to move than the wood stove because the generator has wheels for easy of movement. Ventilation is the lightest and easiest system to move; all the window filters can be detached and are very light to carry. If the family went with Tier 1 instead of Tier 2, the family will have to move the window fan unit instead of the AC unit. The caulk that had been put in the home to help reduce infiltration will have to stay, being the only part of the entire design that will not be portable.

Ergonomics:

The units specified for the designs for heating, cooling, and ventilation, are easy to use. For heating, the owner's manual has instructions on how to operate the stove properly. In addition, when the stove is in use the direct intake cap will need to be taken off the intake pipe, to allow outdoor air to be supplied for combustion instead of the conditioned indoor air. When the stove is not in use, the cap will have to be placed back on the intake pipe to keep unconditioned outdoor air from coming into the home. For cooling, the owner's manual outlines the proper way of operating the AC unit. The AC unit has a simple control system that controls the three levels of fan speeds and the temperature set point can be changed. The window fan has three fan speed settings and a remote control. Reference the owner's manual for further technical operation of the window fan.

Cost Analysis:

Two tiers were created to provide a range of options and try to fit the best suited package for a particular family in Mexico City. The first tier is targeting families at the border of low to middle class income level [5]. This tier still provides the necessary equipment and devices to satisfy comfort needs and ASHRAE standards to improve healthy living, but with less expensive materials. The second tier contains the power generator and the window AC unit. A payment plan will assist families to finance the initial total cost of materials.

Table 4: Cost Analysis of devices, parts and materials for system under 2 tiers.

Tier 2 (high-mid class)		**Tier 1 (low-mid class)**	
Material	*Cost ($)*	*Material*	*Cost ($)*
Stove	$ 376.00	Stove	$ 376.00
Window AC unit	$ 319.00	Window AC unit	$ -
Power Generator	$ 239.00	Power Generator	$ -
Household Tool Kit	$ 59.99	Household Tool Kit	$ 59.99
Exterior Shutters**	$ 100.00	Exterior Shutters*	$ 75.00
Air Filters	$ 16.97	Air Filters*	$ 8.21
Window Fan	$ -	Window Fan	$ 32.96
Zip Ties	$ 2.18	Zip Ties	$ 2.18
4' long 6" stove pipe	$ 135.00	4' long 6" stove pipe	$ 135.00
Hi temp Silicone (furnace cement)	$ 20.00	Hi temp Silicone (furnace cement)	$ 20.00
Bricks (Floor Protector)	$ 17.92	Bricks (Floor Protector)	$ 17.92
Mortar mix (Floor Protector)	$ 20.00	Mortar mix (Floor Protector)	$ 20.00
4" dia. 8' length alum.	$ 15.00	4" dia. 8' length alum.	$ 15.00
Wall adapter	$ 18.00	Wall adapter	$ 18.00
Magnetic thermostat	$ 12.00	Magnetic thermostat	$ 12.00
Flashing	$ 50.00	Flashing	$ 50.00
Storm Collar	$ 15.00	Storm Collar	$ 15.00
9 Self-tapping Screws	$ 20.00	9 self-tapping screws	$ 20.00
12' Extension Cord	$ 17.00	12' Extension Cord	$ 17.00
6" Poly Chimney Cleaning Brush	$ 11.00	6" Poly Chimney Cleaning Brush	$ 11.00
Caulk gun+caulk	$ 129.85	Caulk gun+caulk*	$ 94.85
Sales Tax (16%)	$ 255.03		$ 160.02
Total Price ($)	$1,848.94		$1,160.11