On the other hand, the data that NASA collected was limited to one data point per day. In other words, there was no transient data available; merely an average of the entire day. As a result, simulating the transient effects of a single day in Borko was not possible. Fortunately, the daily averages were sufficient for this project. Thus, the NASA data enabled the technical model to project the needs of the system over the time period in which potatoes were stored.

In addition to predicting how the environment would affect the storage facility, the technical model was used to size the storage structure itself. Given a specific volume of potatoes and a storage method (piles vs. trays vs. bags) the technical model calculated the internal structure volume necessary to hold the potatoes. The output of the technical model included parameters of the storage structure including total volume, roof height, and structure footprint. Additionally, the technical model was capable of calculating how much power would be consumed for a given number of fans and water pumps. The technical model then determined the amount of solar panels and batteries necessary to successfully power the system. In essence, the technical model was able to match the power system with the needs of the cooling system at the same time as it calculated basic building specifications.

## C) Summary of On-Site Data Collection from Borko, Mali

### 1) Local Meteorological Conditions and On-Site Zeer-Pot Testing Results

During the on-site visit to Borko, Mali, local meteorological data was collected. The first of these was solar radiation data. These measurements were taken using a solar flux sensor and a voltmeter. The transfer function of the sensor was:

$$Power\left(\frac{W}{m^2}\right) = Voltage(mV) \times 5\left(\frac{W/m^2}{mV}\right)$$

**Equation 1. Transfer function of the solar flux sensor.**

The data (Figure 8) was collected over the period of an entire day from seven in the morning until five in the evening. Each time a measurement was taken, the sensor was placed facing three major directions: east, west, and vertically.

| Time | Direction | Reading (mV) | Value (W/m^2) |
| --- | --- | --- | --- |
| 7:20 AM | Vertical | 8 | 40 |
| | East | 11 | 55 |
| | West | 5 | 25 |
| 9:45 AM | Vertical | 129 | 645 |
| | East | 201 | 1005 |
| | West | 49 | 245 |
| 11:28 AM | Vertical | 208 | 1040 |
| | East | 193 | 965 |
| | West | 167 | 835 |
| 12:15 PM | Vertical | 200 | 1000 |
| | East | 182 | 910 |
| | West | 121 | 605 |
| 3:00 PM | Vertical | 110 | 550 |
| | East | 67 | 335 |
| | West | 214 | 1070 |
| 4:45 PM | Vertical | 6 | 30 |
| | East | 4 | 20 |
| | West | 8 | 40 |

**Figure 8. Solar radiation data from Borko, Mali.**

Dr. George informed the University of St. Thomas engineering team that these solar radiation readings are some of the highest she has seen.

Because the two locations offered by the villagers (Figures 5 and 6) were not ideal for seed potato storage, a retrofitted zeer-pot structure was selected. A mock-up zeer-pot evaporative cooler was created at the end of the team's time in Borko. See Figure 9 below for a photograph of this style of evaporative cooler.

**Figure 9. Zeer-pot style evaporative cooler created in Borko, Mali.**

Data was taken regarding the ambient environment as well as the results from this temporary zeer-pot structure (Figure 10).

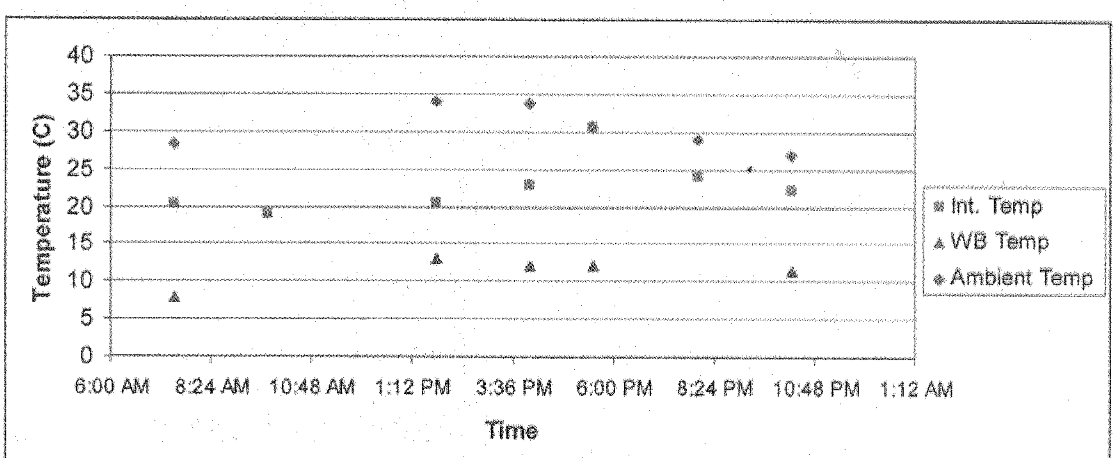


**Figure 10. Temperature data from Borko, Mali and mock-up zeer-pot.**

As shown in Figure 9, the ambient temperature (blue diamonds) ranged from 27°C (80.6°F) up to 34.1°C (93.4°F). The wet-bulb temperature (red triangles) is the theoretical lowest temperature that can be reached by evaporative cooling alone. The internal temperature (pink squares) of the rudimentary zeer-pot ranged from 19°C (66.2°F) up to 30.6°C (87.1°F). The most important piece of information to glean from this small experiment is the efficiency of the zeer-pot. In this case (with little preparation and crudely made materials), the highest efficiency seen was 64%.

**2) Soil Sample Testing Results**

In addition, to the meteorological and zeer-pot data, soil sample tests were conducted while in Borko. Sand is an abundant resource around the village, with different types varying in coarseness and cleanliness. A dried river bed near the village is where the builders collected all of their sand for use in construction. A 200 sieve wash was performed on this sand in order to determine the amount of clay and silt present within the sand. The results follow in Figure 11.

| | |
|---|---|
| Dry Weight (grams): | 130.5 |
| Wash/Dry Weight (grams): | 128.0 |
| Loss (grams): | 2.5 |
| % Passing 200 (%): | 1.9 % |

**Figure 11. 200 sieve wash results.**

Only 1.9% of the material washed passed through the 200 sieve, indicating the sand has only traces of clay and silt present within it. This makes it less likely to transfer particulates to any water flowing throw it.

**3) Revised Problem Requirements**

Although the original problem statement was to cool 15 tons of potatoes with a temperature of 5°C and relative humidity of 95%, after a few conversations with the

Malian agriculture experts these conditions were changed for several reasons. The first design requirement change occurred when it was more clearly communicated that the expected harvest of 15 tons of potatoes would not occur for at least several generations. Therefore, the initial amount that needed to be stored was now only 5 tons. If the design implemented is successful, only then would it be replicated for the additional 10 tons of potatoes.

As stated earlier, preliminary designs involved a compression cycle system that required large amounts of electricity. After meeting with the village leaders, it was learned that the use of a large amount of electricity or any technology that requires maintenance was something they were not willing to do. As a result, the villagers were informed that this decision would make reaching ideal temperatures and relative humidities impossible without electricity. Coincidentally, losses during the storage period would then be inevitable. It was discovered through experiments at the university in Bamako that cooling seed potatoes with evaporative cooling only showed approximately 50% losses. The required storage conditions of the potatoes were then changed from 5°C and 95% relative humidity to 10-15°C and at least 85% relative humidity. Remaining details of the research performed in Mali, as well as various communications with significant expert contacts can be found in the trip report included in Appendix 4, and Appendix 11, respectively.

## D) Design Concept

### 1) Initial Product Solutions

### a) Cooling Methods

The initial problem statement given to the University of St. Thomas design team was "to design a creative cooling structure." At first glance, there were many different options that could have been deemed viable for this problem. Preliminary ideas ranged from simplistic (ice) to more complicated (western style refrigeration). After brainstorming, it was decided that the best cooling option would come from either refrigeration or evaporative cooling. Initially, two different methods of evaporative cooling were researched: water atomizers and humidification columns. The refrigeration method that was explored was compression cycle cooling. It was originally thought that a combination of evaporative cooling and refrigeration would yield the best design.

#### (1) Humidification Column

Humidification columns are a type of evaporative cooler. In a humidification column, dry air enters through the bottom of the column. It then travels upward through the column where it passes through the "filling." These fillings are made of materials that can absorb large amounts of water but are resistant to mold. A water sprayer is situated above the filling and is responsible for saturating it. The dry air encounters this water and begins to evaporate it. The air exits the top of the column at a lower temperature and a higher relative humidity. Excess water pools at the bottom of the column in a reservoir and can then be pumped back into the system. Figure 12 below shows the process of a humidification column.

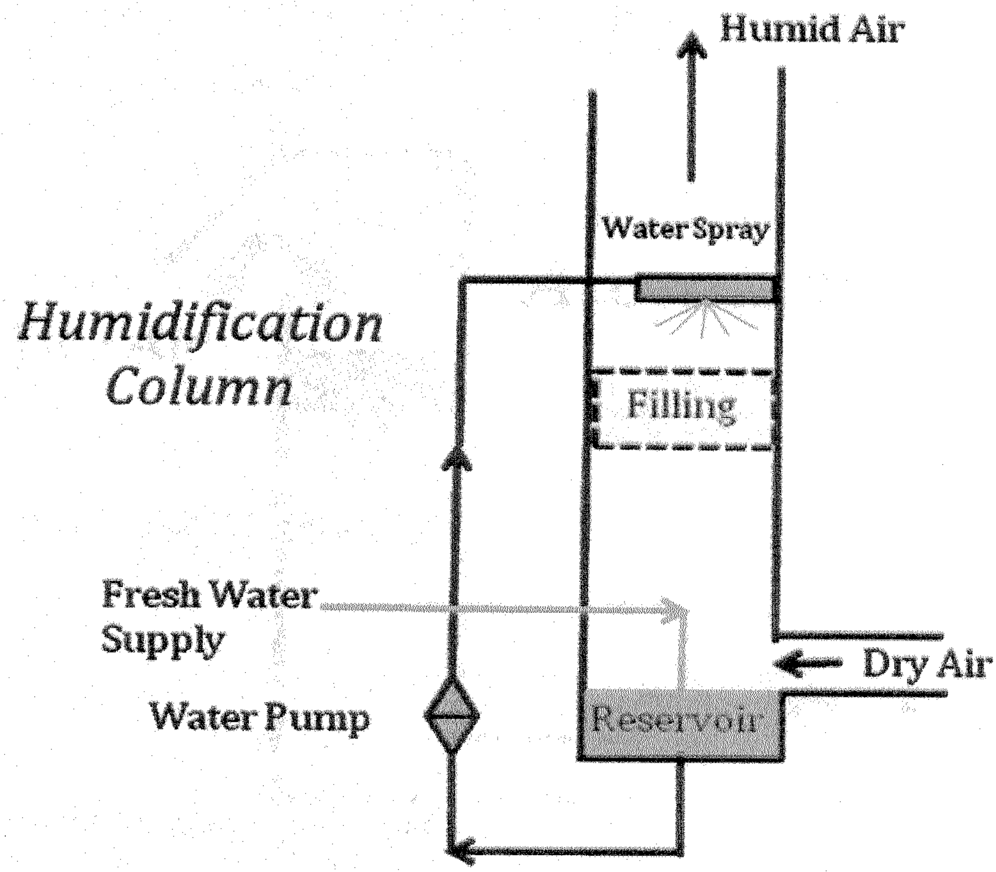


**Figure 12. Diagram of humidification column.**

<u>(2) Water Atomizer</u>

The second type of evaporative cooler that was considered for this study was a water atomizer. Water atomizers are seen in locations that have hot, dry climates. In most cases, water is misted from a nozzle. The surrounding air begins to evaporate the water and the volume of air begins to cool. One issue with water atomizers and potatoes are direct contact. Potatoes can contract disease if they are in direct contact with water. Because of this, a revised design of the water atomizer was researched. Figure 13 shows the revised design that prohibits water from contacting the potatoes. In Figure 13, dry air is vented down a duct and through a water atomizer. This humid, cold air is then pushed through ventilation situated below the potatoes.

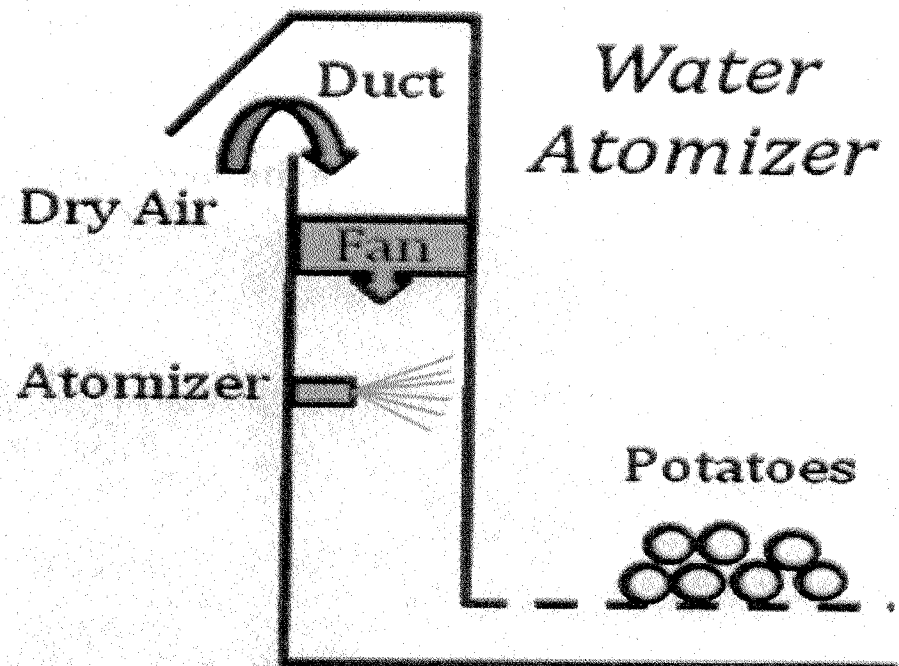


**Figure 13. Diagram of a water atomizer.**

**<u>(3) Compression Cycle Cooling</u>**

Originally, because of western familiarity, the best solution was to use a compression style cooling system. An example of this is an air conditioning unit. If this style of cooling did not need a compressor, this would have been a feasible option. Unfortunately, the large amounts of electricity, the maintenance required for a compressor, and the lack of availability of a refrigeration fluid made this an unfeasible option for the final design. Because of the location of the village and the technical aptitude the villagers, such a complex system was eventually deemed unfeasible. It would require expert maintenance when failures occur and this was simply unavailable.

**b) Power Generation**

To discover all of the possible power generation solutions, a concept classification table was created (Figure 14). This table consists of two major portions: energy generation and energy storage.

| Energy Generation | Energy Storage |
|---|---|
| Wind | Flywheel |
| Solar Panels | Hydro |
| Solar Collectors | Compressed Air |
| Coal | Hydraulic Accumulator |
| Diesel Generator | Spring |
| Natural Gas | Capacitor |
| Compost Heat Generation (Worms, etc.) | Super-capacitor |
| Stirling Engine | Liquid Nitrogen |
| Nuclear | Standard Chemical Battery |
| Mechanical Hand Crank Generator | Flow Battery |
| Hydro Electric | Salt Eutectics |
| | Fuel Cell |
| | Sensible Heat |
| | Latent Heat |
| | Solar Pond |
| | Starch |
| | Glycogen |

**Figure 14. Concept generation table for power generation.**

The left hand side of the table lists all of the possible mechanisms for generating usable energy. This ranges from non-renewable sources like fossil fuels to totally renewable sources of energy like wind power and solar cells. The right hand side of the table indexes all the possible ways of storing the energy that is generated. This is vital for running the cooling system when the selected energy generation source is unavailable. For example, during the night, the sun does night shine. As a result, solar energy generated during the day would need to be stored somehow to effectively run the cooling unit at night.

In addition to the table itself is a color coding system. Any cell that has been colored red is a solution that is not preferable and not possible. The cells that are yellow are solutions that are either preferable but may not be possible OR not preferable but definitely possible. These cells are neither preferable nor possible for reasons that range from lack of funding to lack of skilled maintenance workers. Any cell that is green in color is a preferable and possible solution. The end goal of the concept generation table is to select one item (hopefully green cells) from each column. From the energy generation column, solar panels were selected. And from the energy storage column, standard chemical batteries (deep-cycle) were chosen. See Appendix 5 for Power System Block Diagram.

**c) Structural Integrity Components**

The initial customer requirement was to design a structure which could store fifteen tons of seed potatoes. Some simple calculations were done by using the density of a seed potato and approximations of how the potatoes were going to be stacked in order to determine a rough initial building size of around five meters wide and eight meters long. A concept generation table was then created of possible construction materials. The table is set up in a manner as if a section cut was to be performed on one of the walls of the building. The columns of the table show an outside barrier to environmental conditions, an insulating layer, the structural component and an interior barrier to the humidity.

| Outside | Insulation | Structure | Inside Liner |
|---|---|---|---|
| Brick | Sand | Wood | Metal |
| Metal | Fiberglass | Steel | Rubber |
| Wood | Straw | Mortar | Plastic |
| Vinyl | Spray In | | Vinyl |
| | Foam | | Brick |

**Figure 15. Concept generation table for construction materials.**

The cells of the table are color coded so that each color coincides with the other materials it could possibly be used with. Cells that have no coloring are not viable solutions for various reasons. This includes wood because of the presence of termites in Mali. In addition to this, there are some materials that have the possibility of many combinations. This includes materials like the steel structure that could have a number of different insulating mediums

## d) Controls

To determine the best control solution, it was necessary to determine and evaluate the metrics being controlled. These metrics were temperature, humidity, $CO_2$ concentration, and air circulation. The two most important controllable metrics were determined to be temperature and humidity. These were found to be the most important because they reduce potato loss due to disease while in storage the greatest amount. Once this was discovered, a concept classification table was generated to discover all of the possible solutions for controls (Figure 16).

| Control Type | Control Complexity | Control Theory | Theory Type |
|---|---|---|---|
| Electrical Digital | Single Variable | PID | PID Slow |
| Electrical Analog | Multivariable | On/Off | PID Fast/Overshoot |
| Mechanical | | Artificial Intelligence | Neural Networks |
| None | | | Expert Systems |
| | | | Fuzzy Logic |
| | | | Genetic Algorithms |

**Figure 16. Concept classification table for control structure.**

A control solution that maintained the target temperature and humidity was desired. In order to actively control temperature and humidity simultaneously a multivariable control solution was needed. These two metrics could be controlled separately but since temperature and humidity are dependent on each other, simultaneous control was found to be most effective. Although ideal, a multivariable control is complex and would require a microprocessor based control solution. Due to limited local resources and a desired simple control solution, efforts were focused on designing a control system for only temperature. Humidity would be controlled passively using smart design.

Initially options for complex microprocessor based control systems were researched. While these are energy efficient, they are also extremely complex control solutions. After extensive research and interviews with the villagers in Borko, it was determined that simplicity took precedence over energy efficiency. This was a result of several factors. The first factor was the system operating environment. Borko is a harsh environment where complex systems were more likely to break down faster than simple control systems. The second factor was a time constraint. This control system needed to be completed in less than nine months. A complex control system takes much longer to design and test than simple controls do. The last factor leading the design toward simple controls was the lack of skilled labor in Borko. Since it would be operated by people with limited technical knowledge, a non microprocessor based control solution was the best option.

## 2) Evaporative Cooling Concepts

As stated earlier, the premise of an evaporative cooler is to use the latent heat of water to pull heat from a storage environment. In the case of the zeer-pot designed for Borko, the heat from the potatoes and their environment are driving the evaporation of the water from the walls of the structure. Because evaporative cooling depends on water consumption, the use of water was a sustainability issue for the villagers. As a result, it was important to ascertain how much water the zeer-pot walls would use. Thus, the most important aspect of using an evaporative cooler is the efficiency of water consumption, or in essence, how much water will the design take to be successful.

For most zeer-pot style evaporative coolers, the amount of surface area for evaporation is a determining factor not only in its cooling efficiency, but in how much water it will use. The challenge then lies in verifying exactly how much water a zeer-pot evaporative cooler will use based upon its construction parameters. Different designs for example will have different degrees of exposed surface area, porosity of sand, and insulation mechanisms. For this type of evaporative cooling, the greater the amount of surface area and insulation capacity will greatly affect the efficiency of the cooler as well as the amount of water used to obtain the desired environment.

## 3) Hydraulic and Structural Concepts

The structural model was the second of the two prototypes envisioned. As previously mentioned, zeer-pots are generally made of clay pots. The design put forth in this study can be described as making an extremely large, metal zeer-pot. This kind of design has not been tried and therefore leaves many questions unanswered. The structural model was built to answer these questions.

These initial design challenges included providing efficient sand support, designing a water system, and sand scaling. One of the first challenges that the structural model sought to solve was choosing a proper mesh. It was important that this mesh be able to contain the sand and at the same time have minimal deformation. The second large challenge was designing a water delivery system. This included the entrance of the water into the zeer pot, the exit of excess water from the system, and even wetting of the wall. Sand scaling, the deposit of minerals through evaporation, was a challenge that was not able to be addressed due to time constraints. Looking at this issue would have been problematic since it would take a large amount of time to see the effects of sand scaling. It was deemed that using a filter would solve this problem. In addition to the structural challenges, climate measurements needed to be taken. These temperature and humidity readings were recorded from the structural model. This however was not an initial purpose of the prototype.

**F) Design evaluation through the use of small scale modeling**

To prove that the design that was selected was not only feasible but fully functional, several different small scale models were created. The first of these was termed the "mass transfer model." This model was initially designed to determine both the mass transfer rates of water from the zeer-pot wall to the surrounding air as well as the efficiency of the selected wall configurations.

Additionally, a hydraulic and structural model was completed. This model was designed to prove several things. The first of these were the structural properties of the final design. This included mesh wall designs and wall thicknesses. Not only were structural properties tested, but the input and output of water through the wetted walls was as well. This included irrigation hosing, even wall saturation, and a gutter system

**1) Mass Transfer Model**

**a) Design of Experiments and Variable Definitions**

When designing an experiment, the experimenter is generally concerned with observing how a set of independent variables affects a specific quantity. It then becomes necessary to create a complete design of experiments. A full DOE contains every possible combination of independent variables. This is the only way it is possible to know which one of the variables affects the specific output quantity in positive or negative ways. See Figure 20 below for the complete DOE.

| Trial # | Cartridge Thickness | Wind Speed (m/s) | Fabric Type |
|---|---|---|---|
| 1 | 2.5 cm | 1.5 | 1 oz |
| 2 | 2.5 cm | 2.5 | 1 oz |
| 3 | 2.5 cm | 1.5 | 1.5 oz |
| 4 | 2.5 cm | 2.5 | 1.5 oz |
| 5 | 7.5 cm | 1.5 | 1 oz |
| 6 | 7.5 cm | 2.5 | 1 oz |
| 7 | 7.5 cm | 1.5 | 1.5 oz |
| 8 | 7.5 cm | 2.5 | 1.5 oz |

**Figure 20. Design of experiments with three independent variables: cartridge thickness in centimeters, wind speed in meters per second, and fabric weight in ounces.**

In this case, there were three major independent variables. The first of the variables was wall (cartridge) thickness. It had two possibilities: thin (2.5cm thick) and thick (7.5cm thick). The second variable was wind speed from a fan which came in two options: low speed (1.5 m/s) and high speed (2.5 m/s). The last variable to be tested was fabric thickness. There were two fabric weights: light weight fabric (1 oz.) and heavy weight fabric (1.5 oz). Shown in Figure 20 is every possible combination of the three independent variables.

## b) Diagram and Explanation of the Mass Transfer Wind Tunnel Model

In order to examine the water consumption of different types of "wet wall" designs (Figure 21), a wind tunnel apparatus was constructed (Figure 22).

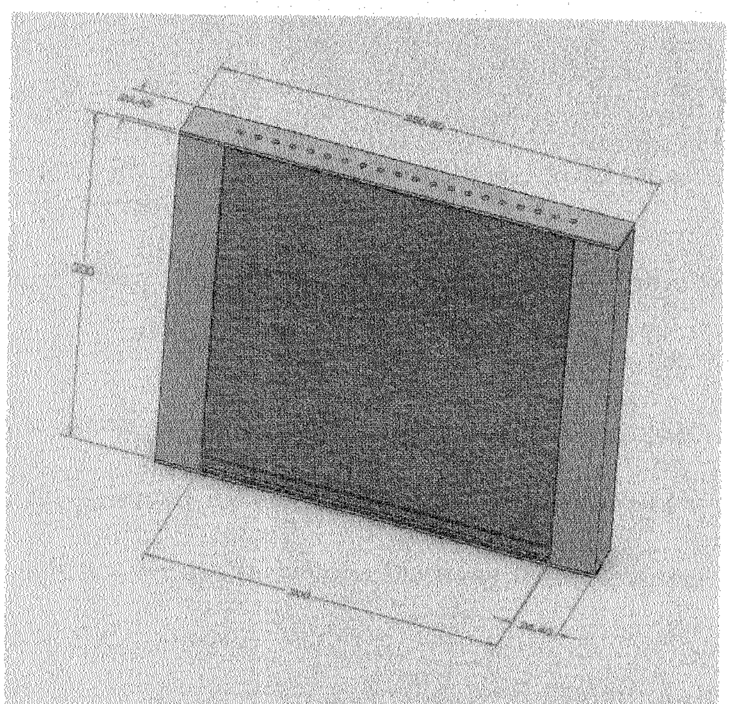

**Figure 21. Cartridge design of various wetted walls.**

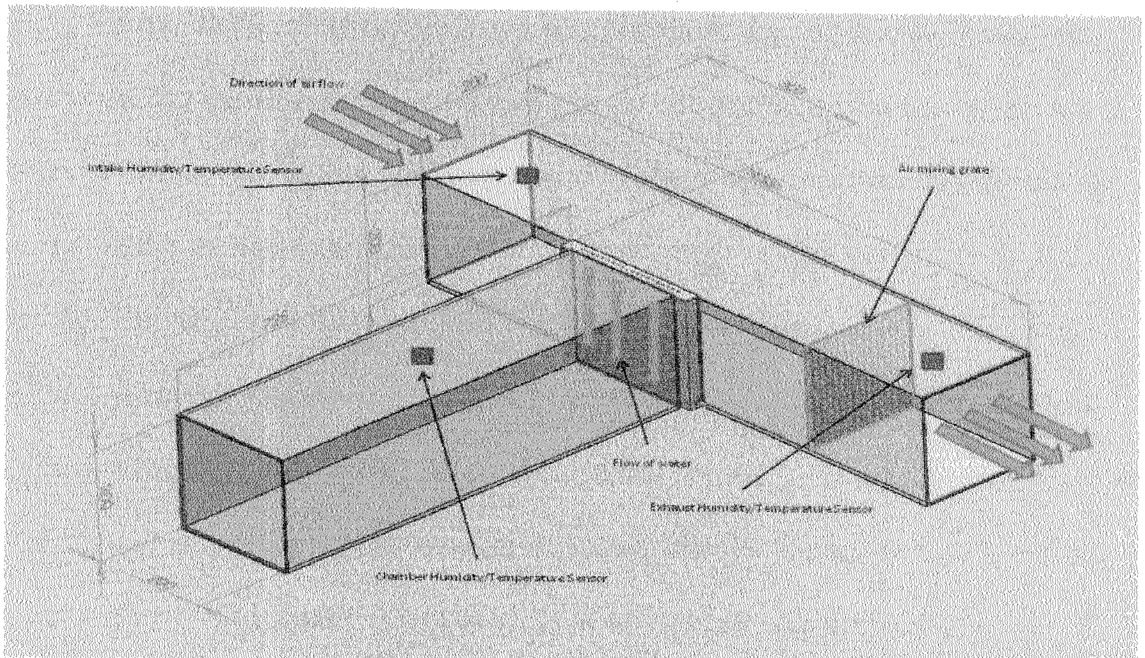


**Figure 22. Entire 3 dimensional CAD diagram of mass transfer model wind tunnel with wetted wall catridge attached.**

Specifically, this determined the mass transfer rate of the water through the porous layer of the wall. The water transfer via evaporation occurred on both the exterior of the zeer-pot as well as into the interior of the zeer-pot chamber. In essence, this meant that the water footprint, given a certain area and volume of a wall, was obtained through analyzing changes in relative humidity and temperature of the wind tunnel and attached zeer-pot chamber.

There were a set of humidity and temperature sensors (thermocouples) in three locations: the intake of the wind tunnel, the exhaust of the wind tunnel, and the zeer-pot chamber. These sensors are shown as red squares in Figure 22. The thermocouples were connected to the Measurement Computing DAQ and the DAQ was connected to the PC. The humidity sensors were connected to the NI DAQ. LabVIEW software was used to monitor and log the data continuously, and is outline in Appendix 7 of this report. The data that was collected was then placed into Excel spreadsheets.

Each of the first eight experiments was performed for approximately one hour, upon which the spreadsheet file of the data was created and the next set of variables was set up. To begin each experiment, five gallons of water were held at room temperature in order to minimize heat transfer to the temperature change of the water. Once the cartridge had its fabric inserted and filled with sand, it was saturated in a nearby sink to test for sand leaks. Once the cartridge was free from leaks and filled with sand, it was inserted between the two sections of the wind tunnel apparatus. The three parts were then held together using nylon straps attached to ratchets in order to keep the cartridge from falling out from between the other two sections of the wind tunnel apparatus.

Once the cartridge was secure, the water distribution cap was placed on the top of the cartridge using Velcro straps with eight, 50 cm long, ¼" diameter tubes connecting the cartridge cap to the 5 gallon water supply container. The water container was placed on an elevated stand in order to create an average hydrostatic head of 40 centimeters above the top of the cartridge.

When everything was in place, the Labview data collection system was started and the valve was opened periodically from the water supply container in order to maintain a saturated cartridge. The excess water was collected in a gutter system below the table and then periodically transferred back into the water supply container. Temperature and relative humidity readings were taken at the three points outlined in the above figure above, which were supplied into the Labview program.

The complete apparatus is show below in the photograph below in Figure 23. The location and orientation of all parts are shown, with the exception of the fan and the wind tunnel entrance ductwork. As shown above in the DOE, eight different experiments using this apparatus were performed. The construction techniques and materials and the data and calculations collected from these experiments can be found in Appendix 6 of this report.

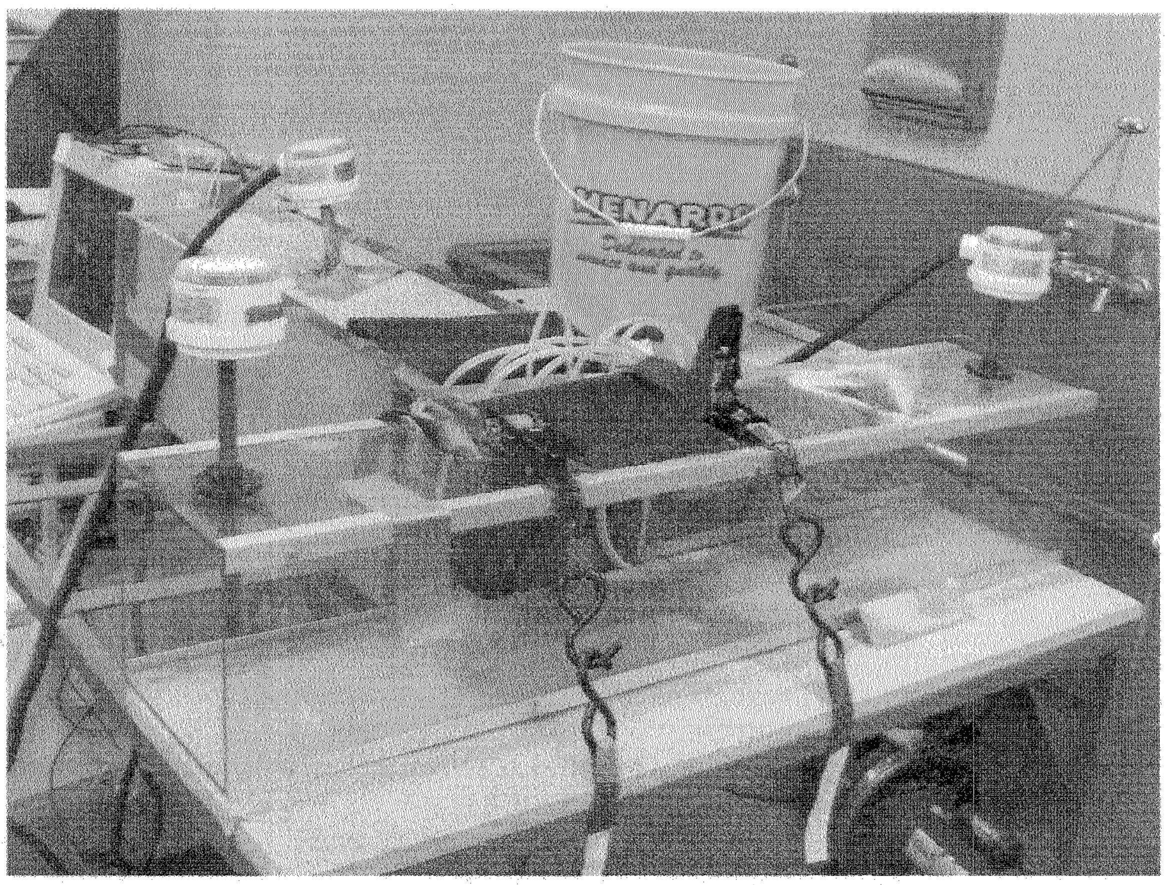

**Figure 23. Photograph of Wind Tunnel Experiment Apparatus**

**c) Fluid Dynamics Analysis and Calculations**

The wind tunnel model used in this experiment was constructed based upon specific parameters of the environment in Mali as well as conditions available in the laboratory. The air traveling along the exterior of the zeer-pot wall had characteristic turbulent flow. This was expected based upon the low and high fan speeds, with Reynold's numbers in the given environment of 13,500 and 22,500 respectively, as well as the surface attributes of the steel mesh walls. (See Appendix 6 for calculations and fluid properties)

In order to simulate the expected wind speeds and characteristics, the fan model that was selected for the final design was used for the wind tunnel to create similar fluid flow in the wind chamber. Based upon the hydraulic diameter of the wind tunnel and the Reynold's number of the fluid, the air was passed through an approximately two meter length of metal ducting in order to simulate developed turbulent flow. By testing the relative humidity and temperature of the air before and after the section of zeer-pot wall as well as in the zeer-pot chamber, the mass transfer rate of water evaporating to the passing air and in to the chamber was obtained. Based upon the selected wall design, an accurate prediction was made as to how much water the entire zeer-pot structure would use.

## d) Experimental Results and Recommendations for Final Solution

Based upon the mass transfer data from the wind tunnel, the rate of mass transfer and water usage was dependent upon the thickness of fabric, the ambient conditions, and the speed of the air passing over the surface. In general, higher air speeds resulted in an increase rate of evaporation as seen in Figure 6.20 in Appendix 6. The thickness of the cartridge had little effect on the rate of evaporation or the level of humidity obtained in the zeer-pot chamber.

Although higher wind speeds caused an increased rate of mass transfer, there was little correlation to increases in humidity inside the zeer-pot chamber. The same outcome was found for the variable thickness of the cartridge. The thinner cartridge actually seemed to have a slightly better effect on the environment of the zeer-pot chamber. Although there were eight variations in the DOE, a ninth experiment was performed for a