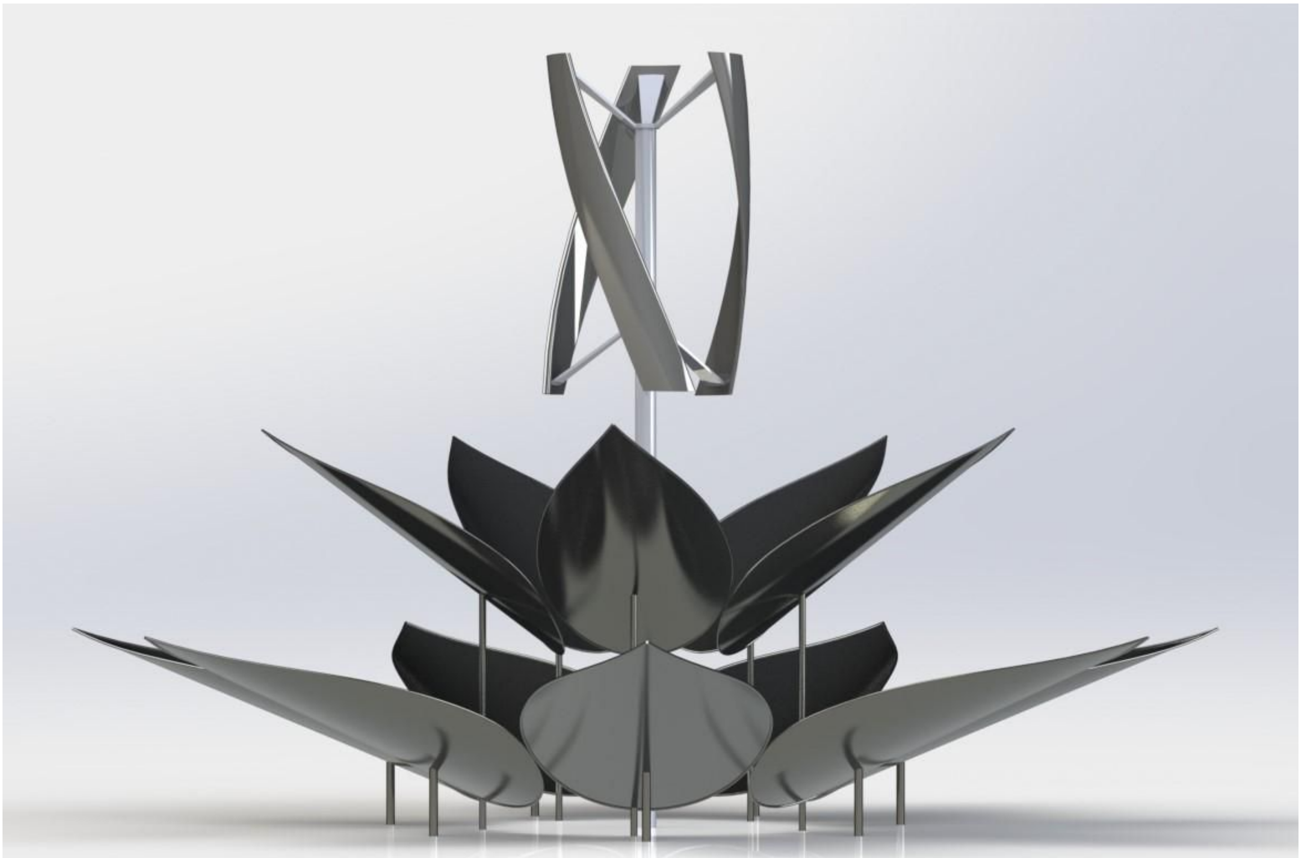
Stratus Designs

Final Project Summary



The Design, Construction, and Testing of a System for Passive Condensation

Stratus Designs: Theo Fedronic, Trevor Hansen, Jack Purvis, Ian St. Louis, Elliot Gutekunst

Vici Labs - Waterseer Competition

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Introduction

With a growing disparity in wealth, health care, and access to resources growing around the world, it is urgent that we assess the means by which we may begin to address these issues. Access to clean water has risen to be one of the most pressing issues in developing nations. Even further, with droughts becoming more commonplace and reservoir levels dwindling faster than ever before, the world is seemingly unprepared for an issue of such gravity. We were inspired to create what we believe will aid in relieving this worldly crisis, and make global access to water cheaper and cleaner across the board. Stratus Designs has come up with an innovative, efficient, and effective solution to the WaterSeer design competition utilizing two proven and researched condensation techniques. It is readily manufacturable, easily installable and cunningly modular.

Inspiration

Our largest design focus for the project was to base our system off of techniques existing in nature, as nature has evolved to perfect these processes. One of the organisms that has inspired our design is the Namib Beetle (Stenocara gracilipes.) This beetle lives in an extremely dry region of the Namib Desert in Southern Africa. The Namib Desert only receives on average 1.4 centimeters of rain each year, yet the beetle is able to survive in this climate due to its unique method of water collection. In the early morning when a thin layer of fog is present in the Namib Desert, the beetle will position itself on a small ridge of sand and tilt its body at a roughly 45 degree angle facing the oncoming fog. Once the beetle has positioned itself on the ridge, its bumpy back surface composed of hydrophilic bumps and hydrophilic troughs attract the water droplets from the fog. This pattern not only helps the water form droplets, but also flattens the droplets helping to reduce the amount of lost water due to wind. We see a very plausible application of this biomimetic process in our design. By adding a similar bumpy surface to the petals, our product would be able to increase its water yield. Methods to create this micro texture can be found in studies done by both MIT and the University of Rochester.

Our Design

The Stratus Designs system is comprised of two main parts - the petal, and the turbine. Each part is independent of the other, modular, simply manufactured, and easily installable. This unique design allows for many opportunities to shape the system to the needs of the environment, depending on variables such as climate and intended aesthetic. Both components produce water independently of each other, but store it in the same, easily accessible manner. In this way, the design is fully functional when arranged in several different sets of conditions, ranging from windy to humid to arid locations.

The Petal

In the construction of the petal itself, the key element was to find the optimal balance of durability and minimized mass in order to reduce latent heat from the sun. We believe that at a thickness of ⅛ inch, the structure will be able to handle any wind conditions with the exception of a hurricane. Our intention in iterating upon the original panel concept was to maximize our water collection potential by making use of rainfall, which is quantitatively far greater in many climates than the amount of water available for condensation in the air near ground level.

To increase the rate of flow from the panel (the ultimate goal of a truly efficient solution) we drew inspiration from the Thorny Devil, a lizard from the scorching heart of Australia that uses the cracks between its scales as a conduit system. It doesn't bow to drink water, as it can pull water against the gravitational gradient and into its mouth passively. We began with the hexagon, a regular geometry which approximated these scales, in designing a pattern for the condensing surface of our petal. In an industrial setting, a stamp could press bio-geometric grooves into the panels before they are curved into petal form. A loosely hexagonal grid combined with a nested set of hydrophilic bumps, taking inspiration from the Namib Beetle, could hold the potential to dramatically increase the rate of flow.

The connection between the petal and the post required a special mounting solution which would maximize the surface area of contact between the two metal units, and therefore maintain adequate heat conduction throughout the system. This connection would also need to be easy to assemble, but also structurally sound. Our spatula design reduces the on-site assembly to a simple twisting motion. During the manufacturing process, a sleeve is slipped over the rod, and attached to an aluminum plate with a few screws. The petal is also fitted with a disk plate that houses the connection. For our working prototype, we used a Type A Machine to 3D print the disk. While this part would likely be manufactured out of aluminum, we were impressed by the disk's structural integrity and detail accuracy. On-site, the petal simply needs to be lowered onto the rod and plate, and twisted 90 degrees, locking it into position. We propose the use of thermal paste, typically used for computer heat management, to facilitate the thermal gradient between the plate and the center of the petal. This design and its practicality are discussed in greater detail in a later section.

The heatsink was designed to be simple for installation by any user, which is why we used a 1 inch square aluminum bar. The temperature of the soil decreases significantly with each foot travelled below ground, but these effects become insignificant after 12 feet. We propose a 10 foot depth for application in very hot climates, but a 6 foot shaft was sufficient for testing in Berkeley. We found that aluminum was the most effective conductor for our price-point, and could be anodized easily to reduce environmental wear. Therefore the panels, heatsinks, and primary pipes are all composed of aluminum.

The Turbine

The second part of our condenser is the turbine. Keeping up with the nature aesthetic, the brilliantly beautiful helical turbine looks like the lotus flower's stigma. In essence, the turbine converts multi-directional wind flow to ductile flow down a pipe and into the ground, where the condensation will take place. The actual mechanism, however, is slightly more complicated.

The turbine itself is to be made of the strongest and lightest material possible, but there are many plastic polymers that would fit the bill. The lighter the turbine's build, the less inertial friction it will add to the system (which functions best with the lightest materials possible). The turbine is rigidly connected to a larger shaft which extends (and connects rigidly) to the first gear on the gear train. Within this shaft is a smaller one which has the freedom to rotate independent of the first. The larger turbine drives the gear train which connects to a gear just below the first one, bound by the same axis in concentricity. This final gear is rigidly connected to the inside shaft, thus allowing it to travel at higher rpm's than the first and increasing effectiveness of the fan below.

The fan is rigidly connected to the inside shaft, and is placed inside, but near the top of the ground pipe. The turbine's rotation will then drive this fan (at the proportionally increased angular velocity), which sucks ambient air outside the pipe into the ground. In doing this, we have begun the condensation mechanism.

Ideally, this initial ground pipe (and the pipe for a few meters after that) would be made out of copper, whose material properties on the microscale allow for the expedient dissipation of air. This dissipation facilitates the removal of water's latent heat of vaporization; a necessary physical barrier in condensing water. Ground around the turbine conducts heat rapidly away from the air (especially in copper and aluminum), providing the chief method by which this latent heat may be removed. This ground pipe channels in a helical formation through the ground, to maximize contact with the cold ground around it in an underground volume that is still feasible to dig a hole for. The piping finally funnels into a sealed, underground reservoir, into which the condensate in the piping drips and then stores.

This method of condensation has immense benefits, aside from its effectiveness. Condensing air in the ground, away from the influence of animals, people, bacteria, viruses, etc. allows for the reservoir environment to stay very sanitary and avoid the direct exposure to nature that typical radiative condensers have. This mechanism also mitigates evaporative losses during the process, as the water is not exposed to thermal radiation from the sun and is stored in a cooler environment (and thus less conducive to evaporation). Finally, adding the water reservoir to the system acts as a strong thermal battery, since the heat capacity of water is so high. As the reservoir fills, the water absorbs the cold from the surrounding ground and becomes a heat reservoir, similar to the earth around it, into which the flowing air can release its heat.

Installation and Modularity

In order to create a truly functional solution, we placed an emphasis on ease of installation and modularity. This allows us to manufacture and install the appropriate system for a wide range of environments. For example, while a full lotus-system is more desirable to resorts for its aesthetic value and productivity, a smaller array of leaves, a half-lotus for example, or even a single petal may be more appropriate for third-world application due to its affordability. The system's modularity was achieved by keeping the core design simple. In fact, the petal and stem can be shipped as only two parts. First, the stem, a long rod, must be driven into the ground. Second, the petal needs to be lowered onto the stem's spatula and twisted into position. Because of the simple assembly, the petal can be quickly removed in the event of hurricane winds. Additionally, the turbine system can be attached to any orientation of petals at any point in time to increase the yield.

Marketing Strategy

The beauty of the Stratus Designs system is its functionality in many different settings. For the luxury market, the system may take on its full, most productive form, using a wide array of petals and copper piping underground to maximize its potential for creating water. This design is aesthetically pleasing, with the shape and appeal of a blooming flower, and fits snugly into any resort or community garden. The petals are also easily scalable, with smaller models being easily adapted, although a larger system acts more efficiently. The petals collect rainfall and condense water while the turbine catches the eye and adds to the efficiency of the system - any resort would catch an envious look from its competitors with a Waterseer centerpiece on its grounds.

For the international market, the system can be broken down into parts and adapted to maximize production of water given the particular climate of the area. An arid location with lots of wind would benefit from a greater focus on the turbine, which pulls air deep enough into the ground to then cool and condense it. A humid location with occasional large storms could benefit greatly from the panels and their collection of rainwater, which could be removed easily before winds reach a speed high enough to potentially damage the system.

This unique customization and scalability also provides many opportunities for entrepreneurial interest. The system can be sold and shipped in only a few parts - the turbine, the removable petals, and the stem for each petal. This allows for simple interchangeability of parts in the luxury market, as petals can be easily replaced if they break. For application in developing countries, there is potential for business revolving around this interchangeability. A town might have its own central Waterseer system, similar to a well, or individuals may have single petals for their own personal water collection and use. If a village were given the tools necessary to fabricate panels on their own, which is a simple process, they would be able to sell the system to neighboring villages and friends, repair broken panels, and alleviate the effects of lack of access to clean water while boosting the regional economy. In another setup, a “water farm” could be created of multiple Stratus Designs systems in one location, which could then sell water to the local people. The possibilities are limitless.

Concluding Remarks

Lack of simple access to fresh water is a widespread and growing epidemic across the world. It affects people globally, from droughts caused by climate change to a lack of infrastructure in developing countries. The Stratus Designs system for passively collecting water tackles this problem, creating a solution that is modular, scalable, marketable, and aesthetically pleasing. It allows for simple installation, is easily manufactured, and is effective in the field. It can create water from the air we breathe, without any external power or influence. It has the potential to create business and combat drought, and it takes its inspiration from life on earth that has adapted to collect water from ambient air. The Stratus Designs system is an overarching answer to not only the problem of bringing clean water to places where it does not exist, but to changing the lives of people around the globe.

Condensed Analysis (full in Apendix)

Gorlov Helical Turbines (the one we implemented) have efficiencies of around 35%. Propellers at high revolutions have almost perfect efficiencies (usually around .9). Our concentric axially rotating turbine and propellor shafts will carry these efficiencies throughout the calculations. Our prop will not spin as fast as the ones in the research did, so it would be reasonable to assume that given the profile of the propeller and its proven efficiencies at high speeds, we can reasonably assume our propeller (bottom fan) to have an efficiency of .75 (rather than .9 at optimal RPM’s).

Some key points before the calculations:

The rate of condensation we have found below can below can be increased with a *decreased* gear ratio on the turbines. However, the gear ratio is necessary to maintain duct flow through the entire underground system. In that regard, the rate of condensation can increase with a decrease in transmission complexity only to the point at which the lower fan no longer provides sufficient flow through the system. Also, a majority of these calculations were made *using energy balance equations*, which is an acceptable representation of this turbine situation as we neglect frictional impact on the system’s energy, and posit that energy from rotation of the turbines and propellers are exactly equal to the shaft work they provide to the system- and consequently, each other.

To begin with, rotational kinetic energy is formulated as $\frac{1}{2}*I*(w)^2$, where I is the quantitative moment of inertia. We found extremely close approximations for each part using SolidWorks, given an *aluminum* build. The mass of the top turbine, using SolidWorks, is 54.7kg, while the mass of the small fan in the pipe is 50g. Their respective inertias are 11.29375 kg*m^2 and 2e-5 kg*m^2-- all of which will be used in the calculations below.

The volume of the air in contact with the turbine is 2.33*10^9 mm^3, or 2.33 m^3. Given air's density is 1.225 kg/mm^3, we can extrapolate that with an 8mph wind flow we have a total energy input to the system of 18.25 J, of which the turbine can extract 35%. Thus, given the energy parted to the turbine and the knowledge of its mass, we can find the tangential velocity of the outside of the turbine to be 33.68 radians/second, or 10.15 RPMs using ½(I_turbine)*(w_turbine)^2 = 18.25*.35, where the right side of the equation is the energy available for the turbine. Given that the whole turbine system is designed to be very smooth running, it is reasonable to assume for this simplistic model a frictionless bearing system, where the only irreversibility bearing on energy conversion is turbine efficiency. The gear train we put forth employs a 1:9 gear ratio- 1 spin of the turbine drives the bottom fan 9 times. Multiplying this angular velocity we get 91.4 RPM's for the bottom propeller. Again, it is clear to us that though the gear train has a 1:9 ratio for RPM's, the shaft work from the top turbine does not directly correspond to shaft work on the bottom propellor (and thus energies as well) given that all real systems have a loss of heat energy due to friction in the system. Since the turbine system is to be as frictionless as possible and made out of cheap but high velocity bearings, we can neglect these losses for the purpose of these calculations.

To find the velocity of the air forced down the shaft, we will take the energy balance ½(I_prop)*(w_propeller)^2*.75 = ½ (m_air)*(v_air)^2 with the propeller's boundaries as the control volume to find the velocity of the air going down the shaft. Note that the .75 on the left side of the equation is the efficiency multiple of the propeller. The mass of the air can be found the same way as above, by taking the density*contact volume of the propellor with the air.

The volume of the air in contact with the propellor is 2.33*10^9 mm^3, or 2.33 m^3. Given air's density is 1.225 kg/mm^3, we can extrapolate that with an 8mph wind flow we have a total energy input to the system of 18.25 J, of which the turbine can extract 35%. The mass of the air in contact is 4.88e-4 kg of air. Thus given the energy parted to the turbine and the knowledge of its mass, we can find the tangential velocity of the outside of the turbine to be 33.68 radians/second, or 321.22 RPMs using ½(I_prop)*(w_propeller)^2*.75 = ½ (m_air)*(v_air)^2. **This velocity is used in the rate of heat convection calculations.**

Heat Convection and Underground Thermal Transfer:
Formula for calculating convective heat transfer of air:
$q/t = hcA\Delta T$
Where $hc = 10.45 - v + 10(\sqrt{v})$

Therefore (by integration with respect to t):
$q = [A\Delta T(10.45t - x\ln(t) + (20/3)(\sqrt{x})(t^{(3/2)})]/\ln(t)$
(this equation can be used to show that longer time in pipe produces a larger heat transfer)

Given:
A = Surface Area of Pipe | **ΔT** = Change in Temperature (above-ground to below-ground) | **x** = length of pipe
t = time of air travel through pipe | **v** = velocity of air (also given by x/t)

For a 20ft length, ½" diameter copper pipe, with a ΔT of 15 degrees Fahrenheit (8.33 degrees Celsius), with the velocity of air being forced down the shaft at 0.5436 meters per second, heat transferred from air by convection in pipe is (using the above formula): 35.02 Joules per second

Heat Equation for Cooling Air:
$q = mC_{air}\Delta T$ | C_{air} = 1.00 Joules / (gram * degree Kelvin)
Heat Equation for Phase Change (Condensation) of Air:
$q = m\Delta H_v$ | H_v = Latent Heat of Vaporization of water: 2264.76 J/g

Given same variables as above,
$q = m(C_{air}\Delta T + \Delta H_v)$
Heat required to condense 3.7L of water: 8.41×10^6 Joules

Combining heat required with heat delivered per second,
Time required to condense 3.7L of water: 2.78 hours

Given current budget for entire system (below), cost of produced water from underground condensation in:
7.6 cents/Liter after one year installed

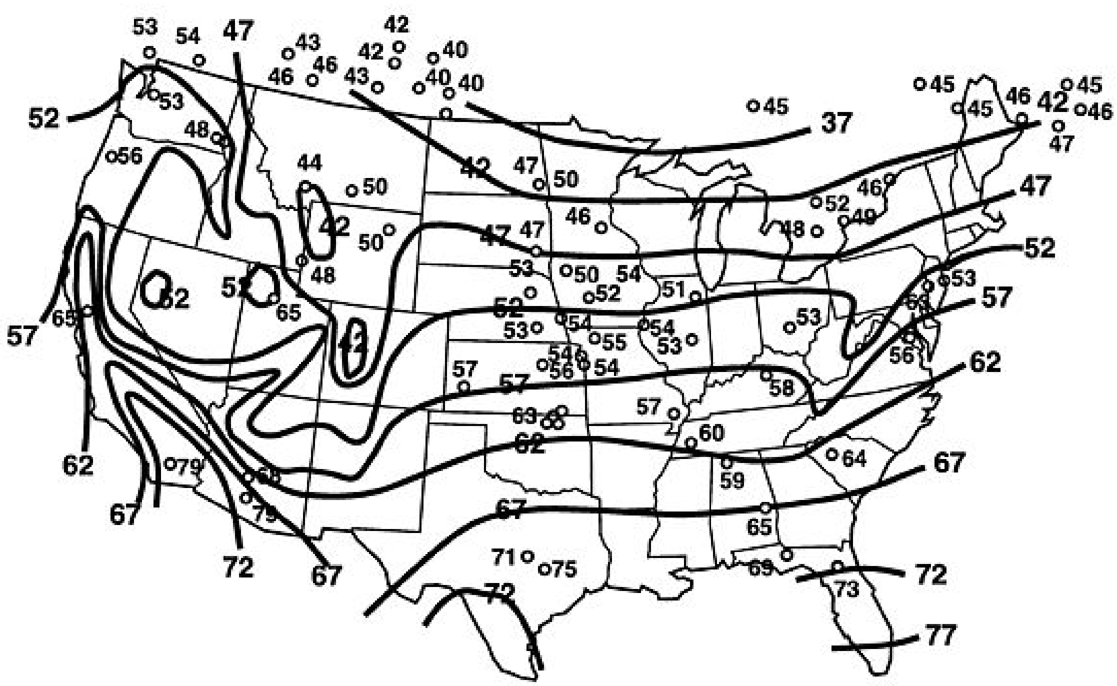
This number is found by simplifying the problem in three distinct ways. First, it assumes that the air molecules present in the pipe can continuously be cooled from their original temperature to produce more water. This is not true in practice, but the slow movement of air through the pipe (0.5436 m/s) ensures that the air which is cooled within the pipe is moved out efficiently so that new, humid air can be introduced. Second, this calculation assumes that there is always available space, on all surfaces within the pipe, for water to condense on. While the pipe will remain cool if it is lowered deep enough into the ground, as water condenses on surfaces it effectively reduces the available surface area for new air to release heat to. Therefore, the efficiency of the system can be maintained by removing water from the inside of the copper pipes as quickly as possible. Third, the earth surrounding the pipe is assumed to maintain its same temperature, acting as an infinite heat sink. While this works over time, the heat added to the earth must be dissipated away from the pipe, lowering the efficiency of the system depending on how hot the surrounding earth becomes.

Overall, these real-world decreases in efficiency would significantly affect the condensation of water within the pipe. However, given the average-value assumed variables, and the resulting impressively high rate of condensation, the output can afford to lose 90% of its efficiency and will still create 3.7L of water in 1 day.

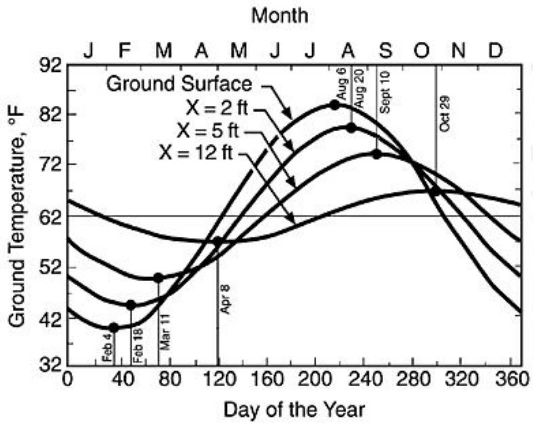
Appendix:

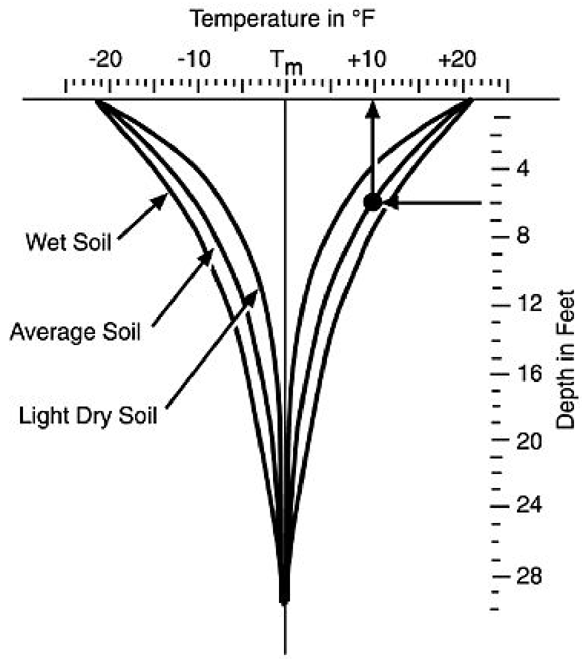
Useful Humidity, Temperature, Rainfall Charts:

Ground Temperature by Region, 30ft depth (at this depth, temperature remains constant year-round)

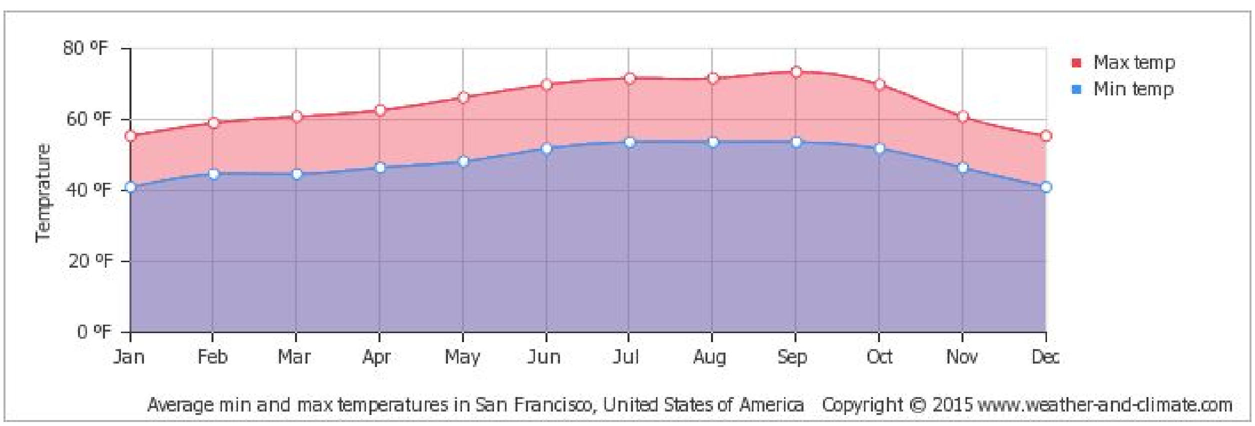


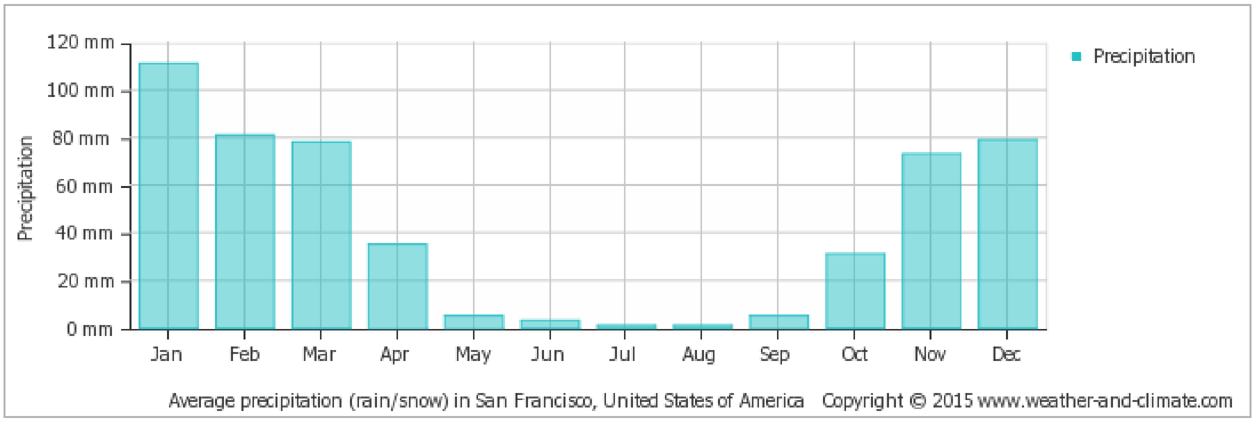
Seasonal Fluctuation of Ground Temperature at various depths:

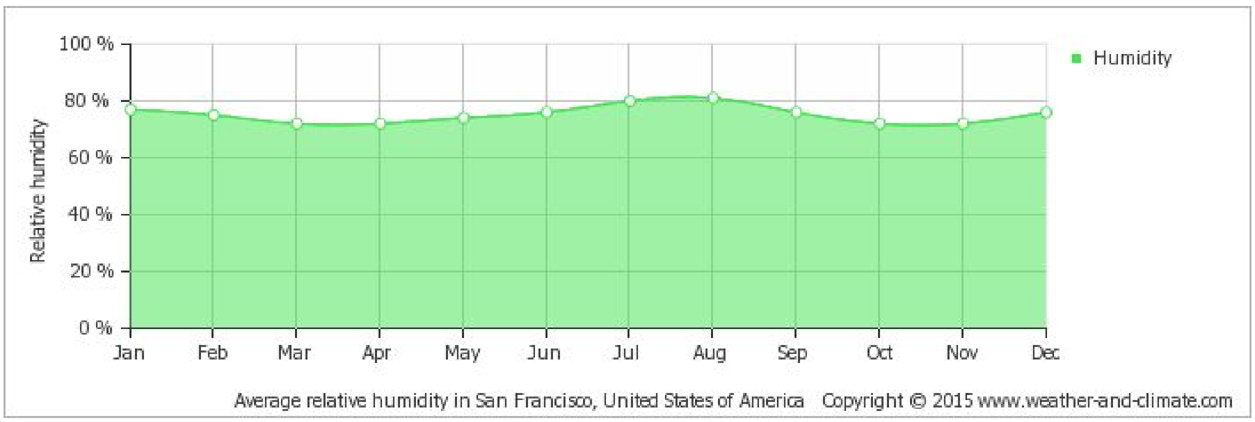




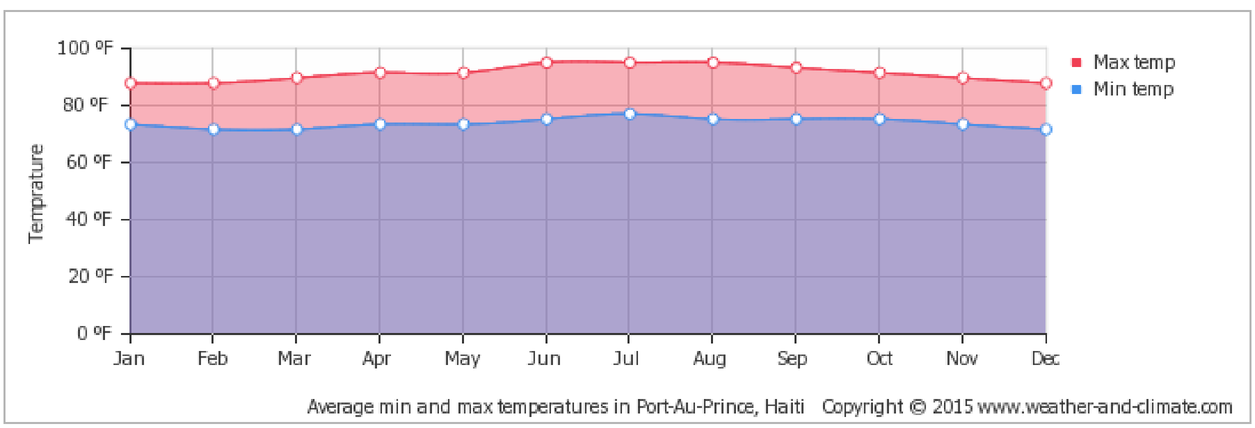
Note that this low temperature in the ground provides cooling when air temperatures jump during the day, although the ground may actually warm the system during cold winter nights. The effectiveness of the panels is incredibly seasonal and climate-based.
San Francisco Climate Info:

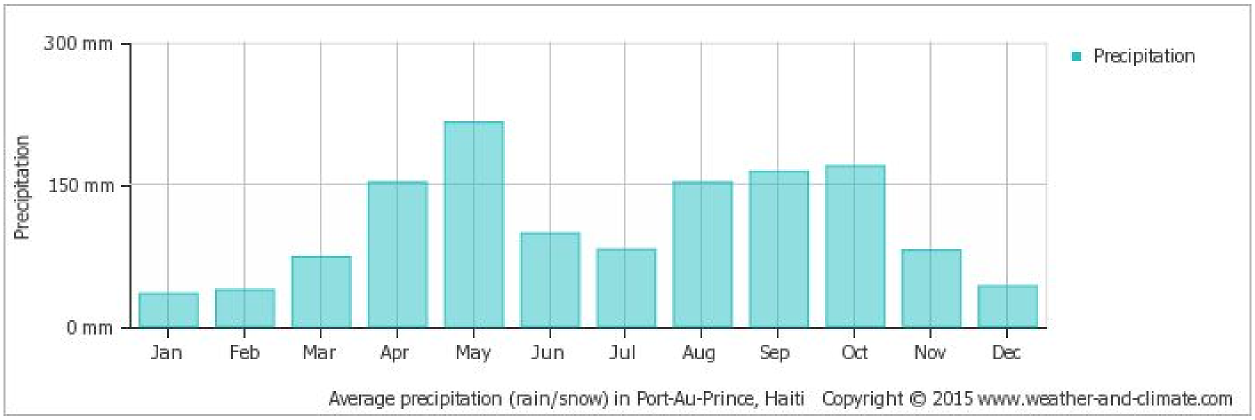


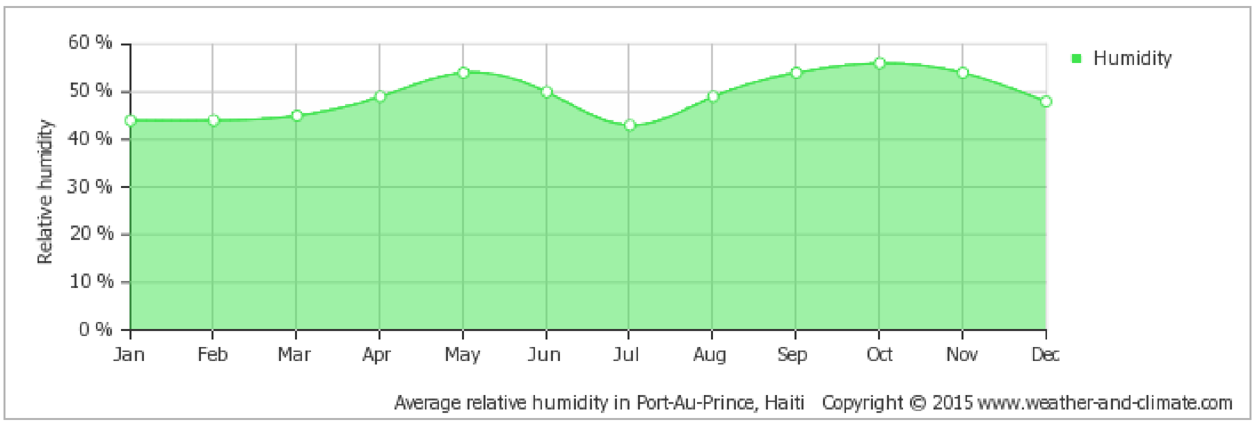




Haiti Climate Info:







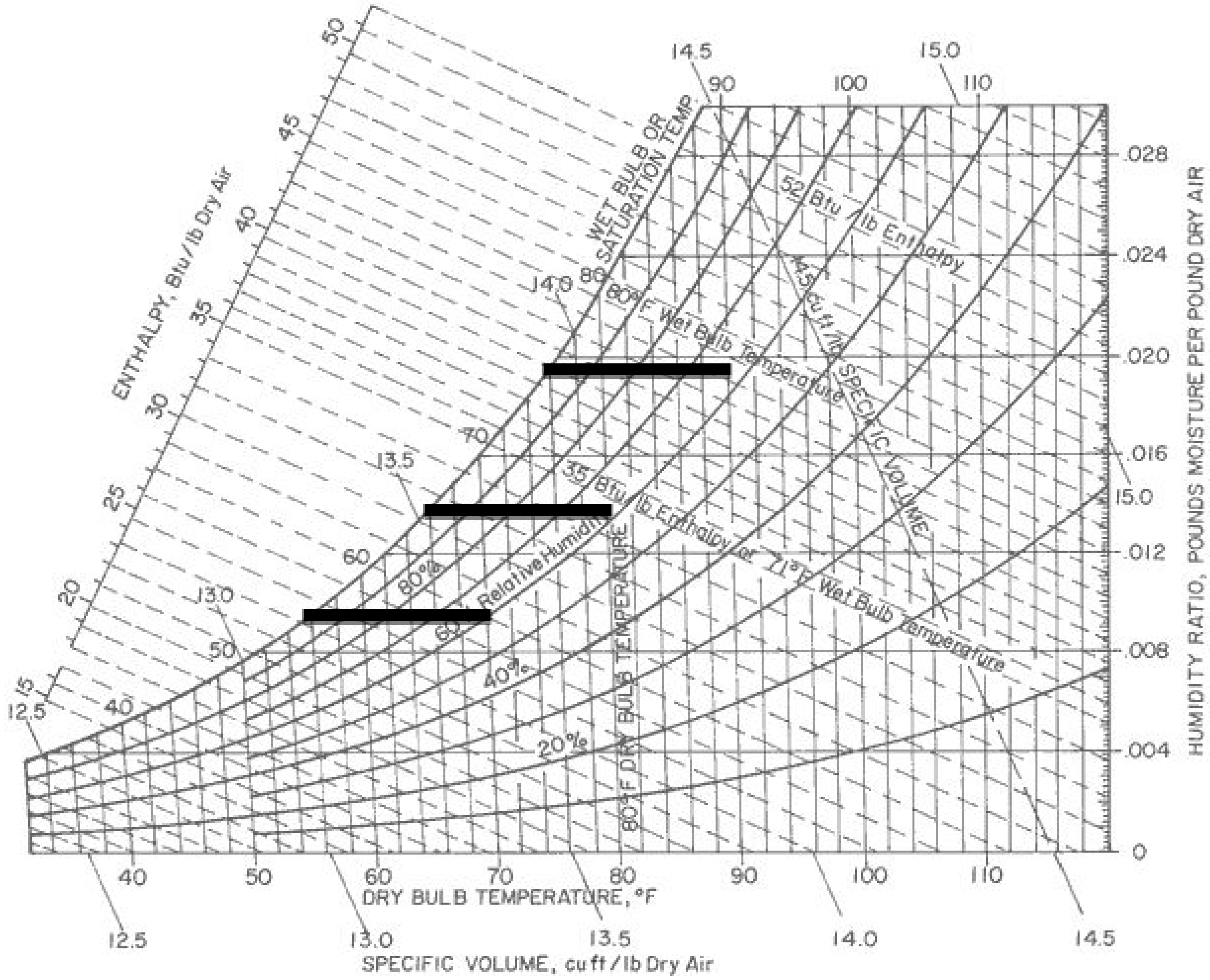
Note however that the humidity on the northern coast of Haiti is much more suited for condensation (shown is Port-de-Paix)

Average Relative Humidity

Years on Record: 112

	ANNUAL	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
%	77	77.5	76.4	75.3	76.1	79.2	77.9	74.5	75.6	77.8	77.8	78.5	77.4

Psychrometric Chart:



The red lines depict a 15 degree F temperature drop to reach dewpoint from 70, 80, and 90 degrees. Note that this is feasible when the air initially has a humidity of ~60%.

Panel Statistics:
Maximum Dimensions: 3 feet by 6 feet
Total Area of cut-out Leaf: 1733 square inches (measured at approx. 67% of original panel)
Total Rainfall Collection Area (Assuming 30 degree angle): 1500 square inches
Average Rainfall in Haiti: 200cm/yr = 78.7 in/yr
Potential Rainfall Collection in Haiti: 52500 cubic inches per year per panel; 860 L per year per panel

Scaling up to 12 panels gives:
10,320 L per year
Given current budget for entire system of panels, cost of produced water from rainfall is:

9.6 cents/Liter after one year installed in Haiti.

These numbers are at a theoretical maximum. Given our panel's performance in collecting rainwater overnight, the following was found:

497mL collected over 931mL rainfall onto surface.
This gives an efficiency of 53% for one test case. This number is likely much higher in overall practice, since the rainfall estimate was based on the 0.09 inches of rain that swept Berkeley in one night, but may not have rained as evenly at the Gill-Tract Farm installation location.

Analysis:

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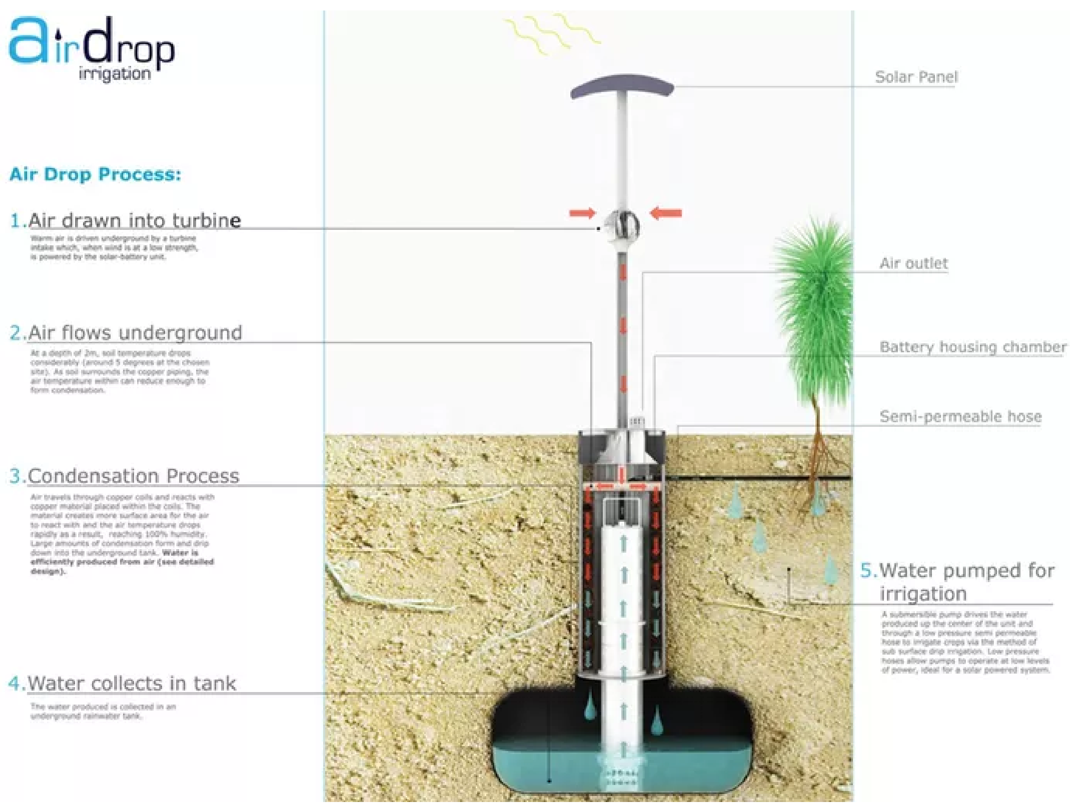
7.6 cents/Liter after one year installed

This number is found by simplifying the problem in three distinct ways. First, it assumes that the air molecules present in the pipe can continuously be cooled from their original temperature to produce more water. This is not true in practice, but the slow movement of air through the pipe (0.5436 m/s) ensures that the air which is cooled within the pipe is moved out efficiently so that new, humid air can be introduced. Second, this calculation assumes that there is always available space, on all surfaces within the pipe, for water to condense on. While the pipe will remain cool if it is lowered deep enough into the ground, as water condenses on surfaces it effectively reduces the available surface area for new air to release heat to. Therefore, the efficiency of the system can be maintained by removing water from the inside of the copper pipes as quickly as possible. Third, the earth surrounding the pipe is assumed to maintain its same temperature, acting as an infinite heat sink. While this works over time, the heat added to the earth must be dissipated away from the pipe, lowering the efficiency of the system depending on how hot the surrounding earth becomes.

Overall, these real-world decreases in efficiency would significantly affect the condensation of water within the pipe. However, given the average-value assumed variables, and the resulting impressively high rate of condensation, the output can afford to lose 90% of its efficiency and will still create 3.7L of water in 1 day.



Turbine System Experiment:

We set out to conduct an experiment that would demonstrate the potential yield of the Turbine Condensation Mechanism. The first part of this system involves a mechanism to draw air into a copper tube. This sub-system is made up of the helical turbine, gear ratio, and boat propeller in a shaft. We built a working prototype of this sub-system that we then successfully tested with a compressed air nozzle. While the full-sized helical turbine was never manufactured, the smaller scale (1:3) turbine that we manufactured using FDM performed exceptionally. The gear ratio, although finicky because of imperfect tolerances and materials, was proven to work and convert the small boat propeller spin speed to 9 times the speed of our helical turbine. This resulted in a slow, but steady flow of air that we later deemed ideal for the success of the whole system. This will be discussed later.

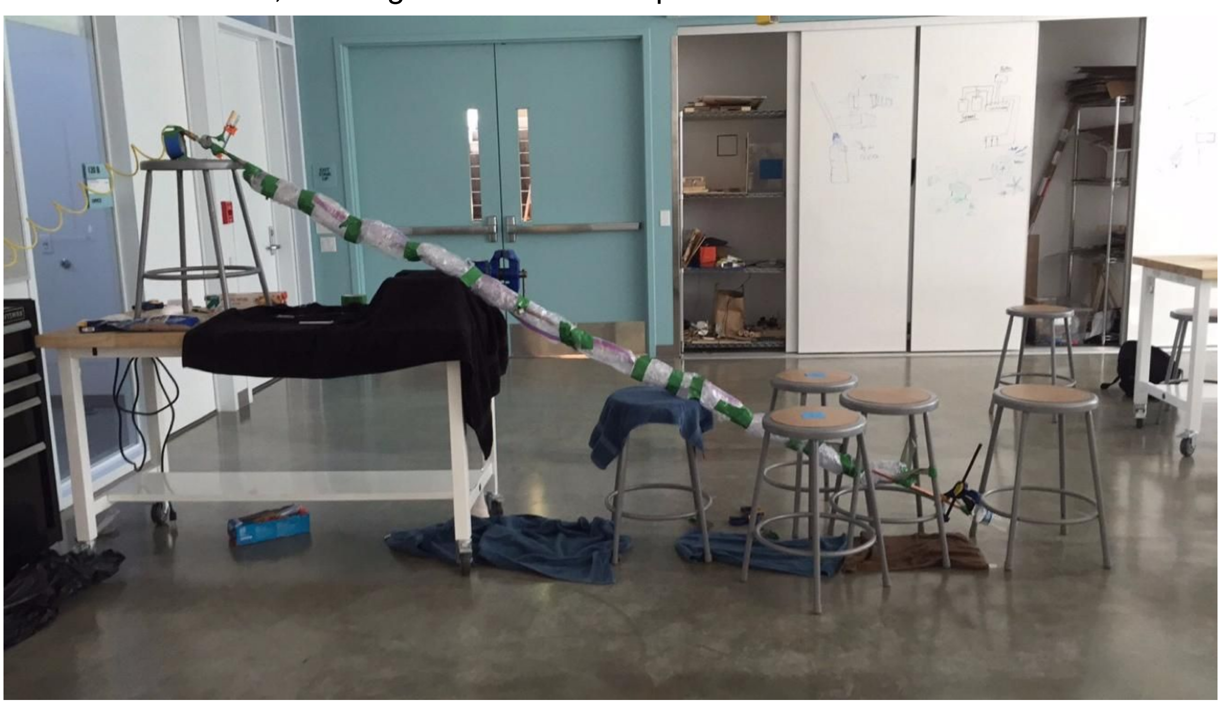
The second sub-system of the Turbine Condensation mechanism, the underground portion, remained untested until today, April 14th. We needed to find a way to push air through a copper coil or tube, and prove that if the copper tube was cooled, it could then sufficiently cool the flowing air until condensation would occur and eventually collect. This was daunting task that we took to right away.

Experiment 1:

Our first experiment consisted of a 10 foot long, .5 inch diameter copper pipe, a compressed air nozzle, bags of ice, a water bottle, and a copious amount of tape. The picture to the right illustrates our setup.

The compressed air nozzle was clamped which gave us full control of the air pressure entering the copper piping. With a slow flow, the air spends more time in the tube, and therefore can cool for longer, giving a higher chance that it reaches the dew point and condenses.
However, because we didn't know the specs of the system that provided the compressed air, we weren't able to calculate the temperature that the air would have to reach.

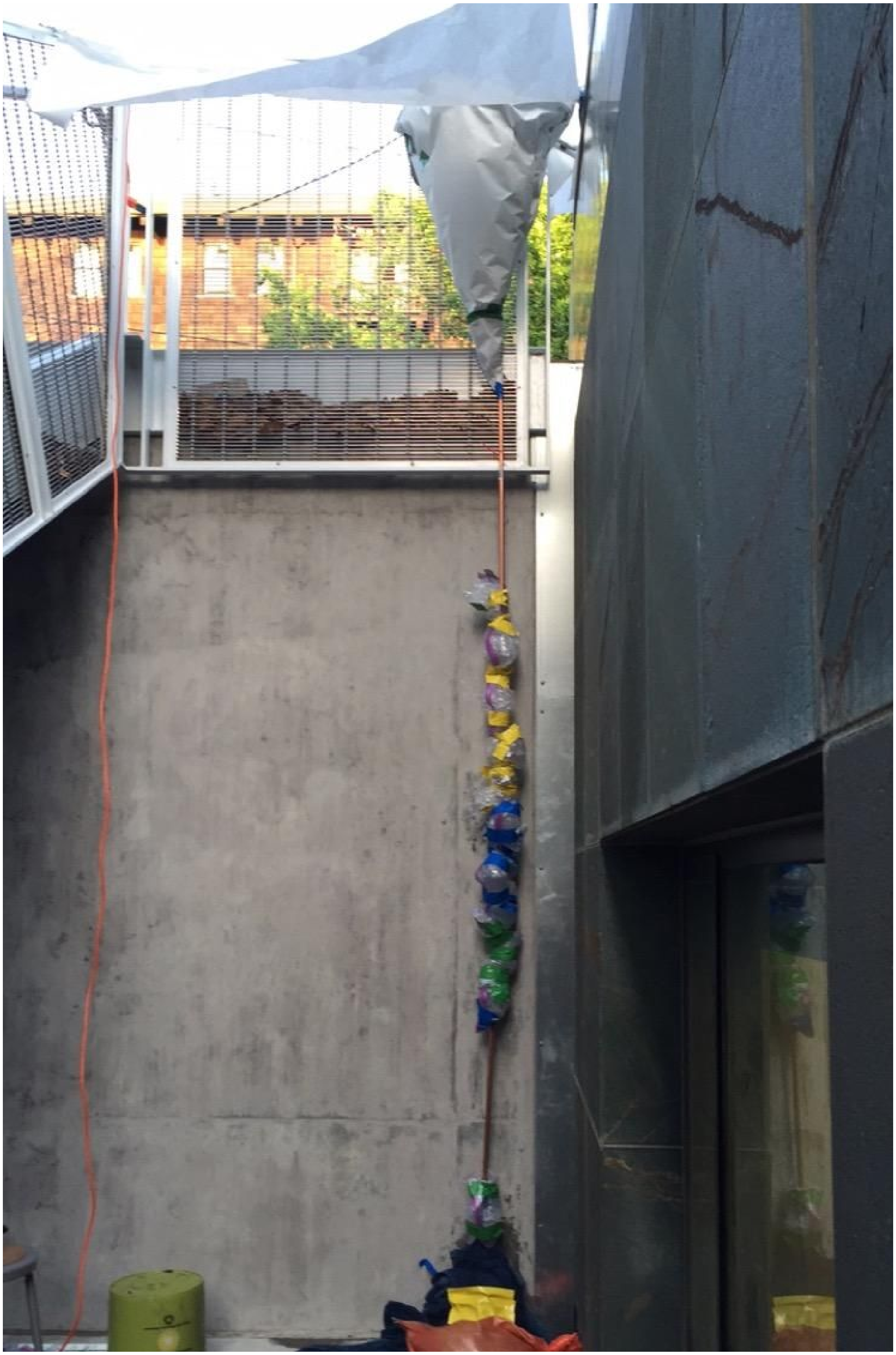
Results: After running the experiment for one and a half hours, we noticed that the exiting air, was very cool, however, there was no noticeable water in the collecting bottle. Upon extensive research, we found that the compressed air had a dew point of about 35 degrees, which decreases further once the pressure is released, creating an infeasible temperature to reach.



Experiment 2: Our second experiment had all the same elements as the first, except the compressed air nozzle was replaced by a large office fan with a large paper cone funneling the air into the pipe. The orientation of the rod was different as well. The image below illustrates this set-up.

The fan had three settings and we found that the lowest setting blew a steady stream of slow-flowing air through the copper tube. We also purchased bronze wool to create turbulent flow within the copper piping, but we could not effectively implement it in our experiment.

Results: As we checked up on this setup, we could see drops beginning to form on the inside surface of the water bottle. After two hours, the water bottle had a small puddle in the bottom, and was peppered with tiny droplets from top to bottom, all around. However, it was a small enough amount that any attempts to accurately measure would be useless by virtue of the measuring technique’s margin of error. As a best estimate, the bottle contained between 1 and 2 mL.



A Note on our Budget:

If you turn to our budget spreadsheet, you will find an appended page (titled "Proposed") which outlines a cost analysis for the full flower unit (12 panels). These numbers were updated from our original budget based on minimum bulk order prices from large scale manufacturers.

We estimate the total material cost of the flower unit at **$995.80**, and our prior cost per liter analyses are based on this conclusion. For our *idealized* total cost per liter produced, we take:

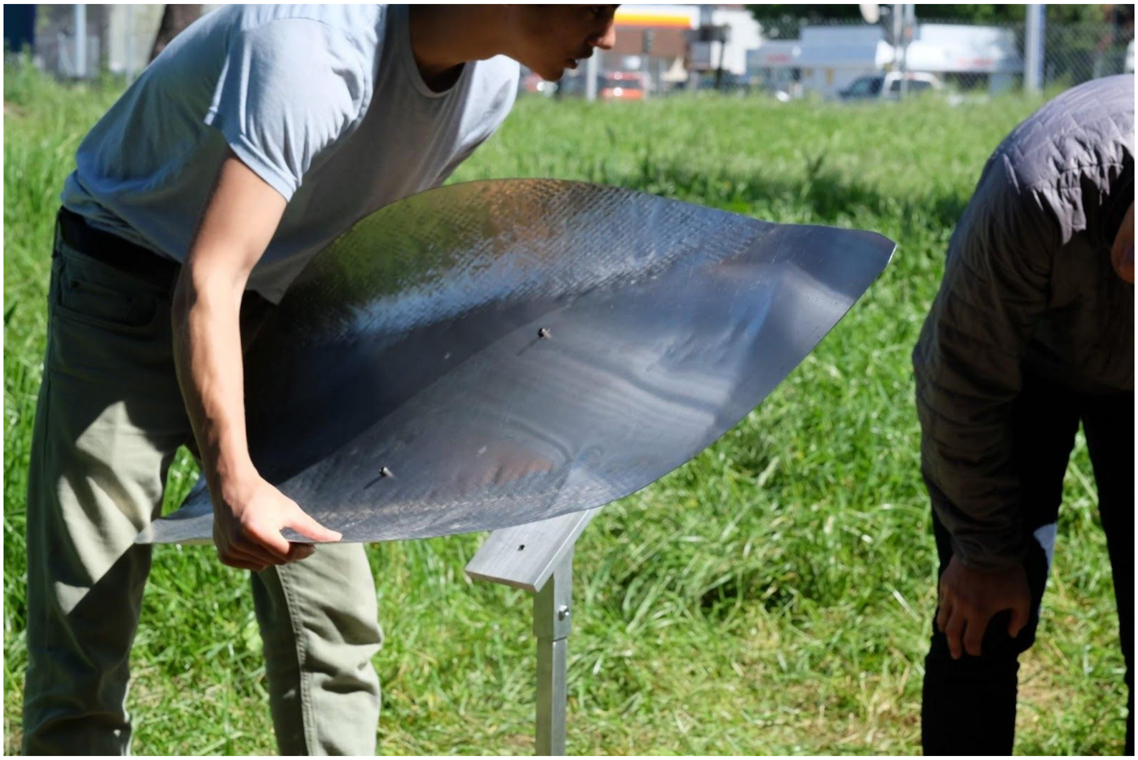
10,320 L per year from rainfall

13,070 L per year from condensation underground

Total cost per liter produced: **4.3 cents per liter after one year** of installation in Haiti

Above photos shows the “spatula” implementation for maximizing the surface area of the connection between the leaf and rod.

The spatula fits into the slot and rotates into a secured position easily and without the use of tools.



Note our most recent model (installed 4/14) features a pitched contour and textured surface for increased flow. We also reduced the thickness of the metal sheet to keep the condensing surface cooler.