

Atmospheric Water Capture in Arid, Rural Environments Using Solid Sorbents

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Abstract

All around the world, there are still hundreds of millions of people who lack regular access to clean, safe drinking water. While there are many ways that various organizations attempt to aid this situation, one promising reservoir from which additional water could be generated is the atmosphere. The technology to collect this moisture exists for higher humidity values but does not exist for arid environments. This project aims to create a device that can pull water out of the air as a drinking source by using solid sorbent materials in an absorption and desorption cycle. It also must be able to operate in rural areas without external power sources, so it will take advantage of a direct conversion of solar to thermal energy. After several experiments and iterative design changes, the device was able to produce approximately 0.5 mL of clean drinking water per daily cycle. However, with additional development of certain components and at a larger scale, this device is a very promising solution for such a prevalent issue.

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1. Introduction

1.1. Background and Motivation

According to the WHO, as of 2017 there were still 785 million people globally who did not have access to even a basic drinking water service, defined as a source free of contamination located within a round trip of 30 minutes [1]. Many people, especially in less developed and lower income areas, are required to travel extensively to gather water, and others still are forced to use unprotected wells, springs, and surface waters that are potentially contaminated. In total, it is estimated that over 2 billion people use drinking water sources contaminated with diseases such as cholera, dysentery, and others [1]. This is also often compounded by a lack of adequate sanitation facilities, such as handwashing stations, in areas where clean water is scarce. For example, approximately 75% of people in sub-Saharan Africa lack basic handwashing facilities [2]. This leads to millions of deaths per year worldwide from waterborne illnesses [3]. This trend is especially true for those in low-income countries, for whom diarrheal diseases are the fifth leading cause of death, and for children under the age of 5, for whom they are also fifth [3], [4]. Even for those who are able to recover, these diseases can cause people to fall behind in education or in their ability to earn money. Fortunately, many of these situations are preventable if clean, accessible water can be provided.

Besides just less developed areas of the world, access to clean drinking water can also be an issue for some even in locations such as the United States. For example, one study has found that from 2013 to 2017 approximately 1,121,100 people in the country lacked a piped water connection [5]. While this is a relatively small compared to the entire population, the same study found that this trend disproportionately impacts people of color. For example, approximately 39.3% of all urban households are headed by individuals of color, but nearly 52.9% of urban households without piped water are headed by people of color [5]. Similarly, the median household income of unplumbed households was only about 51% that of all households [5]. Both of these facts show the lack of access to water is more significantly affecting groups that already face other inequalities. The reasons for these water system deficiencies are varied, including aged infrastructure, unaffordable bills, poor source quality, and more, but in any case, they show that the need for new water sources is an issue impacting all parts of the globe.

While lack of access to drinking water is already a major global issue, it will only continue to worsen if no action is taken. Among various other effects, climate change is expected to continue increasing the frequencies of severe droughts around the world [6]. One study projected that both drought frequencies and drought durations would increase by about 5% with a 1.5 degree Celsius warming in the surface soil moisture [6]. These numbers will vary spatially based on a variety of factors, but the same study projects potential hot spots in North and South America, Australia, southern Africa, and Europe. In all of these areas, these changes likely will lead to even more difficulties accessing adequate drinking water sources.

Given that drinking water is such a pressing issue, the next step becomes analyzing untapped sources that can be developed further when traditional sources such as groundwater or surface waters are contaminated or nonexistent. Some potential solutions, such as desalination of saltwater, can work but are financially costly and energy intensive on a large scale [7]. Another potential reservoir from which to pull water is the atmosphere. Although only a small portion of the total water on earth when compared to reservoirs like oceans, an estimated 12,900 cubic kilometers of water are present in the atmosphere as vapor [8]. While much of this water cycles relatively quickly with other reservoirs, it presents a significant amount of water that is available to be collected directly as a drinking source around the world [9].

Fortunately, the technology to collect water from the air in many areas already exists. When the conditions include high relative humidity (RH), the air only needs to be cooled slightly for the gaseous water to condense. However, when the water content of the air is lower (or in other words, the RH is lower), the difference between the air temperature and dew point temperature, the temperature to which the air must be cooled for condensation to begin, becomes much larger (Figure 1). This means that in these low humidity conditions, water capture using traditional condensation methods becomes energy intensive. This is especially true considering that many of the areas where these new water sources would be most useful may be in less developed and lower income areas with less reliable or established energy sources. For all of these reasons, it becomes largely impractical to use these technologies when the RH is less than about 40% [10].

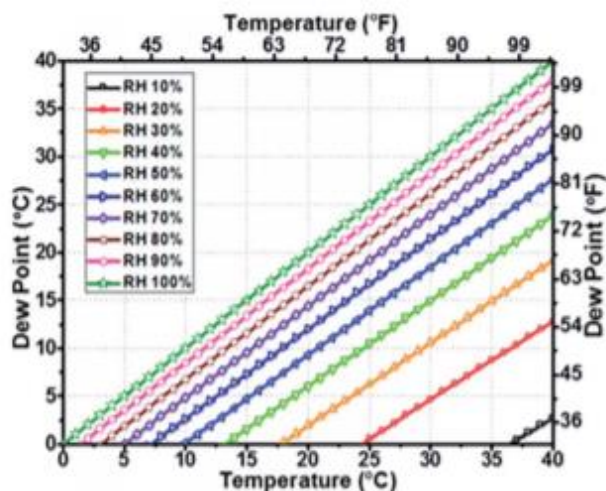


Figure 1 - Dew point temperature vs. air temperature for varying relative humidity values [11]. This figure shows that at under lower RH conditions, the dew point temperature to which the air must be cooled to condense out water is very low. Specifically, for RH values below 40%, which correspond to the arid regions this project is aiming to collect water in, cooling air to the very low dew point temperatures becomes energetically unreasonable. This makes direct condensation very difficult in these circumstances.

Taken together, this information demonstrates a clear need for a different technology that can be used to capture atmospheric water in arid environments. One promising method to fulfill this need is using strong sorbent materials that are known to absorb water well even at lower RH [12]. The details and specifications of this approach will be described later in this report.

1.2. Potential Users and Stakeholders

In the long run, the intended end users of this work would be the populations living in arid regions of the world without access to a clear, reliable source of drinking water. Currently, approximately 41% of the planet's land area is already considered either arid or semiarid, and 38% of the global population lives in these areas [13] (Figure 2). This means there are billions of people who might one day be able to either supplement or completely replace their current water sources with a new technology that gathers it from the air. Especially given the significant challenges many of these people already face and will increasingly face with climate change, providing a new water source that will function even in drier conditions would greatly improve

and potentially even save lives. For these reasons, a successful technology in this space would certainly be extremely impactful around the world.

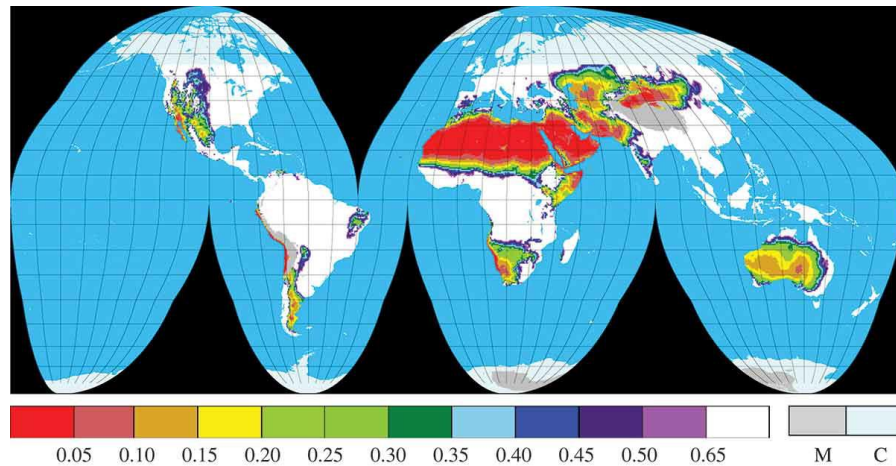


Figure 2 - Geographical distribution of aridity index [14]. Aridity Index (AI) is calculated as the rate of precipitation over the rate of potential evapotranspiration. Generally, an AI between 0.2 and 0.5 is considered semiarid, and anything below 0.2 is considered arid [14]. This map shows that many areas of the world could be helped by a new device that would generate water under these conditions.

1.3. Project Goals

Taking together all of this information on the background, motivation, and potential end users for this project, there are a few clear goals that can be summarized. Most importantly, the aim is to create a new source of clean drinking water for people living in arid regions around the world. Any water collected should follow EPA drinking water standards, which would decrease the prevalence of waterborne diseases in these communities and leave more time for other activities such as education. To make a meaningful change, the volumes of water produced each day should be enough to sustain at least essential activities including drinking and cooking. In order to achieve this vision, the device will need to operate fully independently of external infrastructure, since many arid and rural regions do not have reliable external electricity sources. In this way, the device will be able to provide water essentially anywhere it is required. Overall, if successful this device would make a tremendous difference in millions of lives around the world. Specific technical details on these goals are included in the Technical Specifications section.

2. Exiting Solutions and Previous Work

This project will expand on the work of a previous ES 100 project, completed by Ethan Wong with Professor Scot Martin in 2019 [15]. The previous student designed a device that used liquid desiccant materials (primarily salts) to absorb water from the air, then used thermodynamic cycles to release liquid water from the desiccant solutions. While this project was successful in capturing some liquid water from out of air, one of the primary challenges was that many of the trials did not pass EPA standards for drinking water conductivity and pH [15]. While filtration did help improve these values somewhat, there were still cases where the water did not reach appropriate standards. This therefore presents a potential area for significant improvement, as using other materials such as zeolites may lead to better quality of the produced water. Previous work involving zeolites has found that the material did not negatively contribute to the quality of the water collected used as a sorbent [16]. Any water collected during this project will also be tested to ensure the quality is acceptable, and the standards for this will be discussed further within the specifications section.

Another significant area for improvement from this previous project comes in the form of the energy that the device consumes during its cycles of operation. The design included a thermoelectric cooler, two small fans, and multiple pumps to move water within the device, and over an entire 24-hour cycle required approximately 537 Wh of energy from an electrical grid [15]. This presents a severe limitation on the locations in which this device could be used, as 13% of the world population still has no reliable access to electricity [17]. A new design that utilizes only solar power would still be able to function and provide water in these locations. Even in areas where electricity is already present, utilizing solar energy for the device rather than electricity generated with fossil fuels would help to reduce greenhouse gas emissions. Methods for harnessing solar energy could include solar panels to create electricity or direct conversion of the solar energy to useful thermal energy, and the details of these options will be described further within the design section of this report.

At the same time, there are aspects of the previous project that can be carried over to this new project. For example, some of the general thermodynamic processes used to extract water in the devices will be similar. Just as the salt solutions were heated after an absorption period to release the water [15], solid sorbent materials will also have to be heated to certain regeneration temperatures to release liquid water [12]. While the exact mechanisms might be different for the solid materials, the fundamental concept will be similar. Another aspect of the previous project that will be similar in this project is the sensing of atmospheric conditions at the device. During the testing of their device this previous project measured temperature and relative humidity of the incoming air at all times [15]. This is very important to characterize the conditions under which the device is operating, and therefore to understand under which conditions around the world it would be successful at capturing water. For this reason, similar sensing will be carried out during the testing of this new project.

Besides this previous ES 100 project, other work has been done to explore atmospheric water capture with other kinds of materials besides just salt solutions. One extremely promising group of materials is metal-organic frameworks (MOFs). These have been shown to capture large amounts of water and also have lower regeneration temperatures when compared to most other common sorbents [10]. However, challenges with these materials arise from complicated synthesis procedures. In order to create MOFs that effectively collect water while remaining stable so as not to contaminate the final product, characteristics such as hydrophilicity and pore size and volume need to be carefully tailored [12]. This therefore can require complicated chemical processes to develop appropriate MOF materials.

Another type of material that has been shown to work for atmospheric water capture is zeolites, which will be one of the primary focuses of this project. The most prevalent example of this comes from a group at MIT that has been able to create a device that uses zeolites to capture atmospheric water [16]. Unfortunately, the specific zeolite used in this paper is not commercially available and attempts to contact the group were unsuccessful. However, other types of zeolites are available and potentially useful for this project. The MIT device takes advantage of solar energy to provide heat during the desorption cycle, allowing the zeolite to capture water overnight and then release it when sunlight is available. This strategy is something that will be incorporated into this device's design as well, as being able to rely on solar energy rather than some other power source may be more reliable and less costly in rural, arid areas. Below is a summary of the various sorbent material options discussed in this section (Table 1).

Table 1 - Summary of Sorbent Material Pros and Cons

Material	Pros	Cons
Salt Desiccant Solutions (ex. NaOH or KOH)	<ul style="list-style-type: none"> Widely commercially available. Relatively low regeneration temperatures, in the range of 40-90 C [18]. 	<ul style="list-style-type: none"> Resulting water either requires significant filtration or does not meet EPA pH and conductivity standards [15].
Metal-Organic Frameworks	<ul style="list-style-type: none"> Low regeneration temperatures [10]. 	<ul style="list-style-type: none"> Complicated synthesis procedures [12]. Very high costs [19]. Lack of common commercial availability.
Zeolites	<ul style="list-style-type: none"> Minimal contamination in collected water [16]. Many are widely commercially available [20]. 	<ul style="list-style-type: none"> Wide range of regeneration temperatures [16], [20].

Overall, there is still clearly room for this work on atmospheric water capture to be expanded. Salt based desiccants have been shown to present problems with water quality, making MOFs, zeolites, and other solid sorbents some of the logical next materials to analyze in a device. However, based on the complicated synthesis processes and the scope and timeline of ES 100, MOFs may also not be a realistic option. For zeolites, one challenge will be that there are quite a few different types, with demonstrated regeneration temperatures ranging from about 60 C to greater than 400 C [16], [20]. Initial research and testing will therefore be required to select an appropriate material from all of these options. This process is discussed further in the Design section. The MIT group also identified lowering the cost of the device and minimizing heat loss as two potential areas of improvement from their device [16]. Attempting to achieve these goals, ensuring that the water meets drinking standards, and operating the device only with solar energy would combine the successes of all this previous work into a technology capable of providing water in arid climates. Shown below in Table 2 is a summary of previous projects, their successes and challenges, and how this project fits between them.

Table 2 - Summary of Previous Work

Previous Project	Successes	Areas for Improvement
Prior ES 100 Project, Ethan Wong [15]	<ul style="list-style-type: none"> • Captured water using liquid desiccant solutions. 	<ul style="list-style-type: none"> • Struggled to meet EPA pH and conductivity standards. • Required significant energy from electrical grid.
MOF Based Water Capture [10], [12]	<ul style="list-style-type: none"> • MOFs have high absorption capacities and relatively low regeneration temperatures. 	<ul style="list-style-type: none"> • MOFs are not widely available at affordable rates and have complicated synthesis procedures.
MIT Zeolite Based Device [16]	<ul style="list-style-type: none"> • Uses zeolites to successfully capture water. • Utilizes solar energy as a heat source. 	<ul style="list-style-type: none"> • Device was relatively expensive. • Heat losses could be improved. • Specific type of zeolite used is not widely commercially available.
This Project	<ul style="list-style-type: none"> • This project will aim to combine successes and minimize challenges from these prior projects. It will use solid sorbents which should present less contamination issues, and a much stronger emphasis will be placed on reducing cost and relying on solar energy so that it can feasibly be used in arid regions with less money or where energy infrastructure is less developed. 	

3. Technical Specifications

As discussed in the Project Goals section, the primary objectives of this project will be to generate clean drinking water from the air in volumes large enough to sustain at least essential life functions. It should also not require any connection to external electricity sources, which will allow it to operate in a much broader range of locations around the world. The table and explanations that follow in this section expand upon these goals by setting specifications that are measurable and verifiable for the device that will be produced. At the end of the project, the device's performance will be compared to these specifications to determine its success or areas where it may need further development.

Table 3 - Technical Specifications

Specification	Justification	Best Available
Water pH: 6.5-8.5	EPA Standard [21]	N/A
Water Conductivity: < 1000 μ S/cm	EPA Standard [22]	N/A
Water Metal Levels: Aluminum: 0.02-0.2 mg/L	The Selected Zeolite 3A material is primarily aluminum based, so this EPA Secondary Drinking Water Standard should be met. [23].	N/A
Operating Humidity: < 40%	At these values, traditional condensation methods to capture atmospheric water become much less effective [10].	MOF based devices have been shown to capture water at RH values as low as 10% [12].
Operating Absorption Cycle Temperatures: 10-30 C	There are average temperatures that can be expected in arid environments around the world [24].	N/A
Device Energy Consumption from Electrical Grid: None	This is a potential area for significant improvement, as this new device could operate in rural locations without electricity.	One device used only 2.4 W from an electrical grid in order to power some small fans [16].
Device Battery Specifications Required: 0.96 W/12 V	Small fan specifications [25].	N/A
Incoming Airflow: 40 CFM	After several iterations of COMSOL airflow modeling, this was a reasonable incoming air speed for water collection. An appropriate small fan has been selected. [25].	N/A
Sorbent Material Temperature During Desorption Cycle: 90-100C	This is the rated regeneration temperature of MOFs and Silica Gel materials, and additional testing will be done	Direct solar heating methods, such as parabolic trough reflectors, have been shown to

	to determine regeneration temperatures of any purchased sorbent materials.	reach temperatures of up to 250 C [26].
Water Production: 12.8 L/day	This is based on a recommended daily water consumption of 3.2 liters per person for a family of four [27].	MOFs have been shown to produce water at up to 2.8 g/g, which would therefore require only about 4.5 kg of the sorbent material to collect thus much water [12]. However, these are not being used in this design for other reasons as described in the previous work section.
Device Size: Maximum 0.25 m ³	Various zeolites have a wide range of densities, from approximately 500-1500 kg/m ³ [28], [29]. This means that less than 0.1 m ³ of zeolite would be needed to gather the amounts of water specified above, but the additional volume will allow for the other device components to also be included.	N/A
Sorbent Material Lifetime: 2 months	This is how long a zeolite will last on average before losing half of its capacity to absorb water [30]. The rest of the device should last longer if the sorbent material is replaced.	Some atmospheric water generators can last up to 20 years, but these are ones that operate under higher humidity conditions where water is just condensed through cooling of air. Therefore, they do not deal with deterioration of sorbent materials [31].
Device Cost: \$500	The goal is to build a complete device within the budget of this class; however, every effort will be made to reduce costs even further. The largest cost is expected to come from the sorbent materials themselves.	There is a very wide range of atmospheric water generators, with prices ranging from tens of thousands of dollars for large industrial devices down to small home use devices [31]. As already mentioned, these commercially available devices primarily operate at higher levels of humidity.

The first few technical specifications all deal with the quality of the water that will be collected by the device. pH and conductivity will specifically be measured since the solid sorbent materials that will be used such as zeolites are primarily based on metals. Due to this, it is likely that metals and ions from the material could end up in the water, influencing these parameters. Additionally, levels of the specific metals present in the chosen sorbent will be measured. For example, Zeolite 3A is primarily aluminum based, so this would be a contaminant of concern in

any water that it is used to collect. The standards for these water quality specifications will all be based on the US EPA, since they set well defined and commonly referenced drinking water guidelines [21]–[23]. These standards can all be measured every time that water is collected using specialized meters that are present in the Active Learning Labs. By ensuring that water collected by the device meets all of these requirements, end users can be sure that their water will always be safe to drink and free of strange odors, colors, and tastes that often accompany contaminants.

The next specifications listed define the conditions in which the device must be able to successfully operate. Essentially, these represent the ambient air conditions in the arid environments that this device should be able to collect water from regardless of the design strategy chosen. These include relative humidity being less than 40% and temperature being within the range of 10-30 C. While humidity values less than 40% are generally representative of semiarid and arid climates, this number is really motivated by the fact that most existing atmospheric water capture technologies do not work below this [10]. The temperature range of 10-30 C is an average that can be expected in arid environments [24]. The device may still be able to absorb water with some effectiveness outside of this range, but temperatures during experiments to test the device during this project will remain within this range. In order to monitor these environmental conditions during operation of the device, a joint temperature and humidity sensor will be placed right near the inlet to make measurements of the incoming air. This data can be collected throughout the device's operational cycle during every experiment, ensuring that when the device collects water it is doing so in the intended conditions. These sensors are described more in the Design section. A slightly bigger challenge will be replicating these arid conditions for experimental purposes here in Massachusetts where the average relative humidity throughout the year is between 60% and 70% [32]. One option could be to use a sophisticated atmospheric chamber in a lab on campus that allows for control of all these parameters. If this is not feasible, a dehumidifier unit could be placed near the inlet to mimic arid conditions. While this would allow for less precision in the control of humidity, the sensors on the device would still confirm that the relative humidity is below the desired percentage. Additional details on the chosen method of experimental humidity control are included in the Build section.

Another important aspect of this proposed design is that it should be able to operate in rural areas where an electrical grid is not present. For this reason, the specification for the device's energy consumption from an electrical grid is zero. Any energy needed for the device will come from the sun, whether through solar panels or direct conversion to thermal energy for heating. This is not a specification that necessarily needs to be measured, but rather can be considered successfully met if the device is able to collect water without any connections to a preexisting source of electricity. Design choices will be made specifically to ensure that this is possible and are described within the Design section. One element of this necessary power consumption will come from an inlet fan, which poses a challenge since it will run overnight during the absorption cycle when the sun is not present. Based on COMSOL modeling, it has been determined that an inlet airflow speed of approximately 40 CFM will be appropriate. Based on this, an initial fan has been selected [25]. To power this overnight, a battery will be used to provide energy. Based on the specifications for this preliminarily selected fan, it will need to provide 12 V [25]. This voltage can be reached using 8 AA batteries, for example, since each provides 1.5 V [33]. The COMSOL modeling process is described in more detail in the Design section.

Another design dependent specification is the temperature that the device must heat the sorbent material to during the desorption cycle to release water back out for collection. This is a crucial step in the operation of the device, as the material must reach this regeneration temperature within the device to successfully desorb. These regeneration temperatures are

known for most zeolites and can be obtained from commercial suppliers and existing literature, but vary widely from 60 C to greater than 300 C [16], [20]. For the purposes of this design, the goal will be to achieve interior temperatures of approximately 90 C to 100 C. These are within the range of regeneration temperatures that might be expected for materials such as MOFs or silica gel [16], [34]. This choice also significantly influences which strategy is chosen to convert solar energy to thermal energy that can heat the sorbent. For example, parabolic troughs and flat plate solar thermal collectors are two options that vary widely in the temperatures that they can create [26], [35]. The complete decision-making process for this method is described in the Design section. Once the device is operational, the temperatures reached during desorption cycles can be verified using interior temperature sensors. These sensors can operate continuously throughout the desorption cycles of each experiment and are described further in the Design section.

The amount of water that the device is able to collect is also an extremely important specification, given that the ultimate goal is for it to serve as a drinking water source. The aim will be for the device to produce approximately 12.8 liters of water each day. This number is based on the recommendation that a person should consume approximately 3.2 L/day, along with an assumption that the device should be able to provide for a family of four [27]. By meeting this specification, this device would be able to serve as the sole source of potable water for a household. Zeolites have been shown to have absorption capacities in the range of 0.3 to 0.5 grams of water per gram of zeolite, meaning that approximately 32 kg of zeolite would be needed to collect this much water in one cycle of absorption and desorption in a day [36]. However, due to the costs of zeolite materials and the budget of this project, it likely will not be feasible for the device to use this much sorbent material. For this reason, the fabricated device will likely contain less of the sorbent material, but will demonstrate how the concept could be scaled in the future to collect this larger quantity of water [20]. Volumes of water collected per day can be measured using a graduated cylinder, beaker, or other similar container available in the lab to verify this specification. Related to this is the device size, which should not be larger than 0.25 m³. This number comes from amounts of zeolite needed as just described and the common zeolite densities of approximately 500-15500 kg/m³ [28], [29]. Taken together these numbers show that less than 0.1 m³ will likely be occupied by the sorbent material itself. However, the maximum of 0.25 m³ was chosen to allow for all of the other device components, including the solar absorber technology, to fit. This specification is again simple to verify, as the device dimensions can be measured using a meterstick or similar. Similar to the amounts of zeolite used, the device constructed for this project may be slightly smaller but can serve as a scale model for future versions.

Another important specification is the lifetime of the device, and specifically the sorbent material within it. While the majority of the device's components should be able to function for many years, the limiting factor will certainly be the sorbent material itself. Zeolite materials have been shown to lose half of their absorption capacity after about two months of daily absorption and desorption cycling [30]. This means that the material would need to be replaced approximately this often by users in order to continue collecting water. This specification may be difficult to concretely verify based on the relatively short timeline of this project, but one method could be to track whether the amounts of water collected decrease after several consecutive trials. This would be an indicator of the absorption capacity decreasing, and the data could be analyzed to infer when the capacity might be reduced by half.

One final specification will be the cost of the device. Since the target end users who live in arid, rural areas often may also be low-income, the goal will be for this to remain under the ES 100 course budget of \$500. This is due to the fact that one of the most expensive components of the device will certainly be the sorbent materials. These vary relatively widely in

cost and availability, from less than 50\$ to several hundred for the amounts that would likely be necessary [20]. With all of this said, every effort will be taken to keep costs to a minimum. Complete costs for all components purchased will be included in the final Budget, and these considerations are also be reflected in the Design section. This is another easy specification to verify by just tracking the costs for all of the individual components and summing them at the end.

4. Technical Design

4.1. General Device Design

The overall method for this device to collect water from the air operates on two cycles. The first will be an absorption cycle, during which the sorbent materials will absorb water out of air that is being pulled into the device. This will take place at night by default since the other cycle must operate during the day. This second cycle will be a desorption cycle, during which the sorbent materials will release the previously absorbed water in a usable form. To achieve this, the sorbent materials must be heated to known regeneration temperatures (also referred to as desorption temperatures), at which the water is released. This heat will come from a direct conversion of solar to thermal energy, motivating why this cycle must take place during the daytime. Figure 3 below shows which components of the device operate during each of these two cycles, along with a few that operate throughout both. More details on the operation of each cycle are provided below.

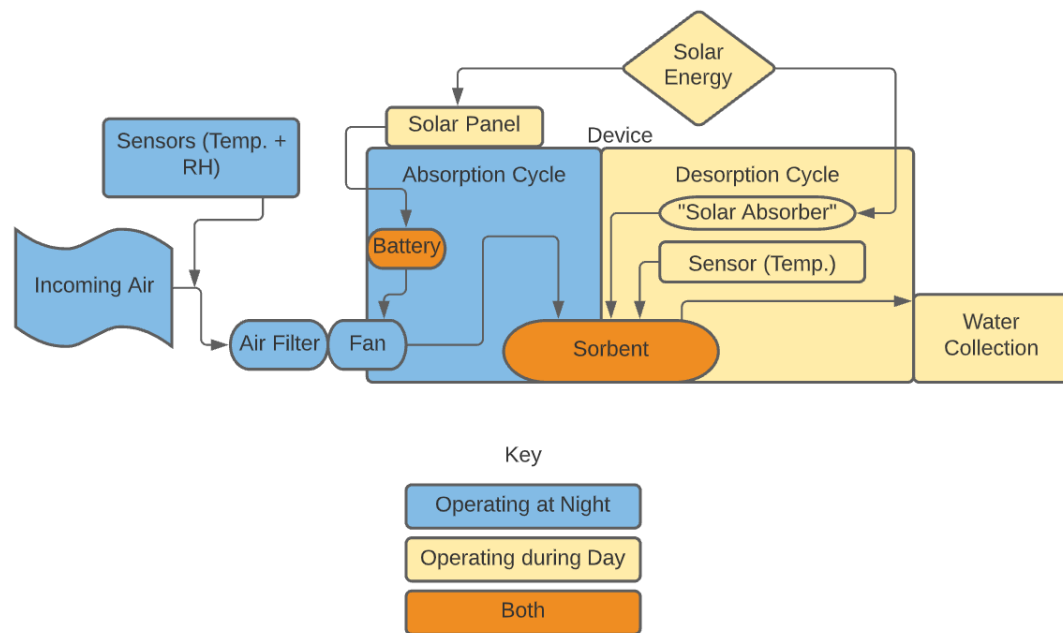


Figure 3 - This system diagram includes all of the device's primary components as well as how they will interact with each other. The device will operate on two cycles: an absorption cycle overnight where water is taken from the air, and a desorption cycle during the day where the sorbent materials are heated to release the water in a usable liquid form.

As stated above, the absorption cycle will take place overnight so that the desorption cycle can operate during the day when solar radiation is available. During this absorption cycle, a fan will run continuously to pull external air into the device interior. This will be powered by a battery that was charged by solar panels during the day. Sensors will be located directly adjacent to this inlet, allowing constant monitoring of the air's temperature and humidity. This data will allow verification that the device was operating in the target conditions that accurately represent arid regions around the world. Additionally, in order to protect the fan and interior

components from small particles like sand or dust that might cause them to degrade more quickly, an air filter will be placed right before the fan. Once this air has finally entered the device, it will be directed to flow past the sorbent materials. This is where water will be absorbed and stored in the materials until the desorption cycle.

Once water has been absorbed overnight, the desorption cycle will be able to take place during the day. During this process, the sorbent material must be heated to a specific regeneration temperature which depends on the properties of the chosen material. This allows the water to be released back out and collected for use. In order to achieve this temperature increase while also meeting the requirement of not using an external power source, solar energy will be converted directly to thermal energy. I have chosen to do this using a flat plate solar thermal absorber, which will be located at the top of the device. More details on this design are included later in this section. Once the water has been released from the sorbent, tubing will direct it to a final collection point on the exterior of the device. Being on the exterior will allow any gaseous water to condense into a liquid, since the temperature will be lower. More details on this collection mechanism are also included later. Finally, a solar panel will also be collecting incoming solar energy throughout the day. This is stored in a battery to then power the fan during the desorption cycle as mentioned above.

One final aspect of the system diagram shown in Figure 3 above is that a couple components will operate at all times, during both the absorption and desorption cycles. First, a battery will be charged during the day by solar panels, then power the small fan overnight to draw air into the device. The other, and probably the most important element of the device, is the sorbent material. This is what captures water out of the air and then holds it to be released later. Characteristics of these materials such as their absorption capacities and desorption temperatures will directly impact the operation capabilities of the device, and therefore choosing an appropriate material is critical for success. This decision-making process will be explained fully in the following section.

4.2. Sorbent Material Selection

As described above, the selection of a sorbent material is a crucial step in determining how well the device will be able to perform. Since these materials will be involved in both the absorption and desorption cycles, materials need to be chosen that can both hold significant amounts of water but also release it at temperatures that are reasonable to achieve. In order to select appropriate sorbent materials for this device, a few characteristics were considered. The first of these is the absorption capacity, or how much water can be held. These values describe how much water can be held per mass of material, with an example being that most zeolite materials can hold about 0.3-0.5 g water per g zeolite [36]. These numbers can be found in the literature and from suppliers of the materials, but I will also test the absorption capacities of any materials purchased to verify them. Another important factor to consider is the desorption temperature, or the temperature to which a material must be warmed to release out the large majority of the water that it has absorbed. Similar to the absorption capacities, these numbers can be found from suppliers and in previous literature but will be verified in the lab. Finally, the other factors considered were cost and commercial availability. While important based on the budget and timeline of this project, keeping these factors in mind is also very important in ensuring that this technology would be accessible to the people around the world who need it most as a drinking water source.

By considering all of these factors, research led to a variety of potential materials that were either used in previous literature or were available from commercial suppliers. It was immediately clear that there was a very wide range of desorption temperatures between various materials, which therefore could have a very significant on the device's design since it must be able to reach the given temperature for the selected material/s. For example, some types of zeolites had regeneration temperatures rated at a few hundred degrees Celsius [20]. While not impossible, high temperatures like this would present a very significant challenge to achieve. On the other hand, some materials such as the Zeolite AQSOA Z01 or silica gel had regeneration temperatures under 100 C, which is a more feasible value to obtain. Regeneration temperatures for a variety of materials are shown below in Table 4. This table shows values gathered from suppliers and literature, but experiments will be performed to verify them for the selected materials.

Table 4 - Sorbent Material Regeneration Temperatures

Sorbent Material	Regeneration Temperature (C)
Zeolite 3A	175-260 [20]
Zeolites 4A, 5A, 13X	200-315 [20]
Zeolite AQSOA Z01	~60 [16]
MOFs (Metal-Organic Frameworks)	55-85 C [37]
Birnessite (MnO ₂)	~87 [38]
Silica Gel	~80 C [34]

Based on this desorption temperature information, it was possible to draw a few initial conclusions. First of all, the category of zeolites 4A, 5A, and 13X was eliminated since they had the highest temperatures. This left a few options, with zeolite AQSOA Z01 and MOFs seeming like the best choices based on desorption temperatures. Unfortunately, for both of these materials there would be other significant challenges. For zeolite AQSOA Z01, it seemingly is not available anywhere to purchase commercially, and was only found in one academic paper (LaPotin et al. [16]). Attempts were made to contact the authors of this paper, but after not receiving a response about their source or fabrication methods, it was necessary to eliminate it. For MOFs, these desorption temperatures as well as their very high absorption capacities of up to 2.8 g water per g material made them a very promising option [12]. However, as a relatively novel category of materials there were not many suppliers available and those that did exist were extremely expensive. For example, one quote for MOF-801 came in at \$500/100 mg or \$6,000/50 g [19]. While outside the budget of this project, high costs would also be an issue for any device that would potentially be distributed to less developed regions of the world. Additionally, attempting to synthesize these materials personally would have required a significant effort and length of time that would not fit within this project's scope. Therefore, although these materials had many of the optimal characteristics for this application, they also could not be used.

This leaves a few other options from Table 3, including Zeolite 3A, Birnessite, and Silica Gel. The zeolite and silica gel are readily available from a variety of sources online at reasonable costs, and therefore should not present any issues in that way. Birnessite was also available from some suppliers, although it was most often provided in sheets or larger chunks

rather than beads or a powdered form like the other options [39]. These formats would be less compatible with the interior design configurations that are described later in this section, so Birnessite was also eliminated from consideration. Therefore, by elimination Zeolite 3A and Silica Gel were the final options. In order to confirm that these would be reasonable choices given the project's goals, one of the final research steps was into their capacities to absorb water at lower humidity values. As can be seen in Figure 4 below, the abilities of each of these materials to absorb and hold water depend on the relative humidity. Around 40% RH, the upper end of the goal operating range, the zeolites and silica gel have approximately equal absorption capacities. However, as RH continues to decrease to lower values the zeolites are able to hold slightly more water. It is also important to note that in this figure CaO is shown to absorb more water in low RH conditions than either of the selected materials. However, it was not ultimately selected due to its slower rates of absorption [40]. Even though its maximum water capacity may be higher, this is not useful if the material takes significantly longer to reach the same amount of water absorbed.

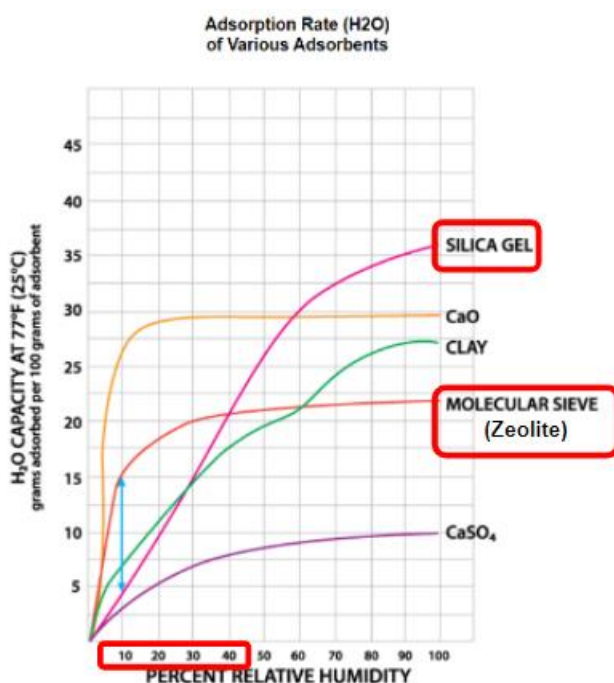


Figure 4 - Absorption capacities of various sorbent materials at varying relative humidity values [40]. This shows that around 40% RH, the silica gel and zeolites are approximately equal, although at lower humidity values the zeolite materials can hold more water. Materials and RH values of interest have been highlighted in red.

With this information, it becomes clear that there is a tradeoff between the silica gel and the zeolite 3A. While zeolite materials can hold greater amounts of water at low RH values, they also need to reach temperatures about 100 C greater than the silica gel to let that water back out so that it can be used. For this reason, it was ultimately decided that both of these materials would be purchased and tested within the device. Taken in combination, these two materials might also have the benefit of simulating how an optimal material such as a MOF might be able to perform in this application. For example, by looking at the absorption capacity of the zeolite and the ability of the silica gel to desorb, a better understanding of how one material with both of

these optimal characteristics might perform can be obtained. Then, if materials like MOFs became less expensive and more accessible in the future, they too could possibly be used in devices to collect drinking water from the air.

In order to verify the characteristics of these two chosen materials, certain experiments will be done before they are tested with the entire device. First of all, an experiment will expose these materials to air, allow them to absorb, and measure changes in mass to determine their water absorption capacities. The hydrated sorbents will then be placed in an oven and heated, with mass being changed over time. This will help to determine at which temperatures most of the water is released from the sorbents. If all goes well, these results will confirm the rated material characteristics and support other design decisions. The procedures for these experiments will be explained in more detail later in this report.

4.3. Solar Thermal Absorber Design

As has already been stated, these sorbent materials must be heated to certain regeneration temperatures in order to release any water that it has absorbed. However, there are a variety of methods that can be used to increase a material's temperature. Many of these were eliminated immediately due to their utilization of some external electrical power source, which would have violated the stated goal of having a device capable of operating independently of anything like this. Even without these however, there are still multiple methods which can be used to convert incoming solar radiation directly to thermal energy. For example, one option that was considered was a parabolic trough. These configurations take advantage of the fact that a parabola made of a reflective material such as mirrors will use reflection to concentrate incoming solar energy on one central point. For example, these are often used to heat water in a pipe in the center of a parabola in a variety of industrial applications, and have been shown to create temperatures upwards of 600 C [41]. Even on a smaller scale in a rural environment, one group was able to achieve temperatures around 250 C using one in southern Africa [26]. This latter value is probably closer to what could be achieved by this project but is still certainly high enough to desorb the selected materials. However, to be most successful the sorbent materials would have to be located at the exact point where the light was concentrated, and it would be crucial to minimize all other components that might block the incoming light. This would make holding the materials and collecting the water during the desorption cycle significantly more complicated, and therefore another suitable option was ultimately chosen to heat the sorbents. This final choice is known as a flat plate solar thermal absorber and is shown in Figure 5 below.

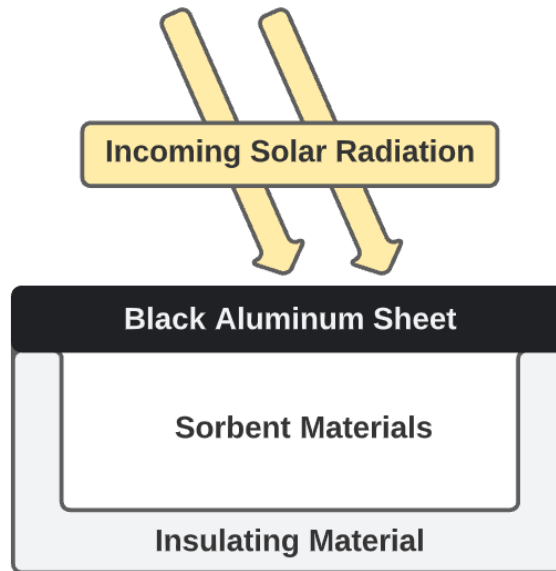


Figure 5 - A representative Flat Plate Solar Thermal Collector, adapted from Witmer [35]. Incoming solar radiation will hit a black, metal sheet which then conducts the heat into the insulated interior of the device. This will allow the sorbent materials to increase in temperature and release the absorbed water.

This design functions by having incoming solar radiation hit and be absorbed by a black aluminum plate. This material was chosen to be aluminum since this is a metal that conducts heat relatively well. It will also be painted black to decrease reflectivity and increase the absorption efficiency of the material. This will maximize the amount of incoming solar radiation that it will be able to absorb. From there, this heat is transferred to the interior of the device, where the sorbent materials will be located. This will allow their temperatures to increase so that they can reach their desorption temperatures and release their absorbed water. The interior will also be completely lined with an insulating material in order to minimize heat losses to the surroundings and maintain high temperatures within the device. This type of design has been shown to heat stationary materials, as the sorbent materials will be, to temperatures of around 80-90 C [35]. These values will also be verified experimentally after this section of the build has been completed. It is important to note that this temperature range likely will not achieve significant desorption of the zeolite 3A sorbent, which has a significantly higher regeneration temperature. However, this should reach the regeneration temperatures of the silica gel, and the Zeolite 3A will be used to demonstrate a material with greater absorption capacity. Its desorption will still be characterized in an oven, and together the results of both of these materials will hopefully simulate how a MOF material would perform if available.

4.4. Water Collection Mechanism

Once the solar thermal absorber has warmed the sorbent materials to their regeneration temperatures, the other critical component of the desorption cycle will be capturing that released water in a usable form. For example, if the materials were just open to the surrounding air during this desorption cycle, then the water would just be returned back to the air it was initially absorbed out of and would be no more useful to the end users than it was initially. Therefore,

the device's interior must be configured in a way that will be able to collect this water. To achieve this, sorbent materials will be located within a pipe inside of the device. They will not entirely fill the device, allowing air to still flow past, but this will allow the water to remain better contained. This pipe will be slightly tilted, with a slope of approximately -0.12 from the front to the rear of the device (the higher end of the pipe will be at the front near the inlet). so that released water will flow in one of two directions rather than remaining stagnant. Liquid water will flow downwards within the pipe, while and vapor will be directed upwards in the opposite direction. Located at each end of the pipe will be funnels to gather this water and direct it into narrow plastic tubing. These tubes will then use gravity to direct the water to one final collection point on the exterior of the device. Being on the exterior serves two purposes: the temperature there will be cooler so that any vapor can condense into a liquid, and it is also more easily accessible for users. Modeling and diagrams of this interior configuration can be found in Figures 6 and 7 in the following section.

4.4.1. Device Interior Modeling

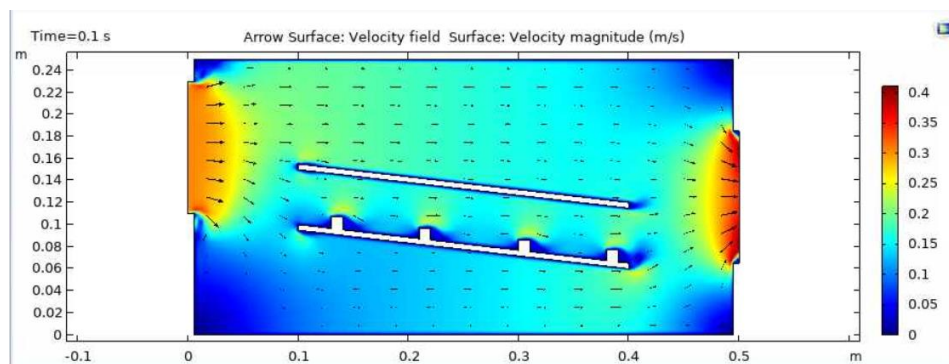


Figure 6 - COMSOL airflow model of the device interior. After several iterations changing locations of various components, this final iteration was selected as it allows consistent airflow through the pipe where the sorbent materials will be located. Ridges along the pipe interior are to hold the sorbent materials in place while the pipe is sloped. Inlet speed is set at 40 CFM.

Shown above in Figure 6 is the final iteration of a COMSOL airflow model for the device's interior during the absorption cycle. Certain simplifications were made in this modeling process, including the decision to model in two dimension rather than three. Since the design of the device does not have much variance in the third dimension, this was a reasonable choice to make. Additionally, certain components are not included in the model for simplicity. This is because the primary goal of this model was to ensure that the sorbent materials within the pipe would receive consistent airflow from which they can absorb water. In the model, the left wall simulates a small fan, with the incoming air speed being a model input. This is shown as 120mm high, which serves to represent the size of a common small fan [25]. The right wall includes an open boundary, which allows air to passively flow out, and on the interior two rectangles simulate a lengthwise cross section of the pipe where the sorbents would be located. Along the bottom of the pipe are several ridges, which will serve to hold the sorbent materials, so they do not just slide out of the slanted pipe. Simulations began with the wall openings and pipe all at heights halfway up the device, and after several variations of these placements it was determined that this placement of the fan at a height of 0.11 m from the bottom and the pipe

opening at a height of 0.1 meters made sense. At this point the ridges had not been added, and the flow through the pipe was uniform along its entire length.

The ridges were then added to ensure that these small structures would not impede the air as it flowed over the sorbent materials. At this point, all important components are included since components such as funnels from the desorption cycle will not be present during the absorption cycles that this is modeling. While this added some slight variation to the air speeds observed at different locations, it seems that the materials still will be exposed to airflow. In fact, the speeds being slightly lower between the ridges is likely beneficial since the sorbent materials will have slightly longer to absorb water out of the air. The inlet speed was also varied over several iterations to simulate different kinds of fans, and it was ultimately decided that a speed of 40 CFM would work well. As shown in the model, this leads to an average velocity of roughly 0.18 m/s within the pipe. This means it would take the air about 2.78 seconds to travel through the device. This time is expected to be slow enough so that water is absorbed but quick enough that new air with additional water is brought in often. However, this pattern of operation could be an interesting area of future work. For example, it would be useful to analyze if a better cycle would involve turning the fan on and off regularly. This might allow greater amounts of water to be absorbed from that air, and then new air would be drawn in once that air is mostly dry. It is currently unclear whether this method would absorb more water per time than the current operating cycle of consistently bringing in air.

Based on these conclusions, the configuration shown below in Figure 7 was decided upon. This diagram shows the inlet fan, outlet opening, and pipe as in the COMSOL model, with a few additional components also included and called out. For example, the funnels and tubing to collect recently desorbed water are shown at each end of the PVC pipe. The tubing to the final collection point will be directed through the outlet to a final collection point to the right of the device. This figure represents the originally conceptualized interior configuration, although several small changes were later made based on initial observations and test results during the build and verify steps. These iterations are described in detail in the Build section.

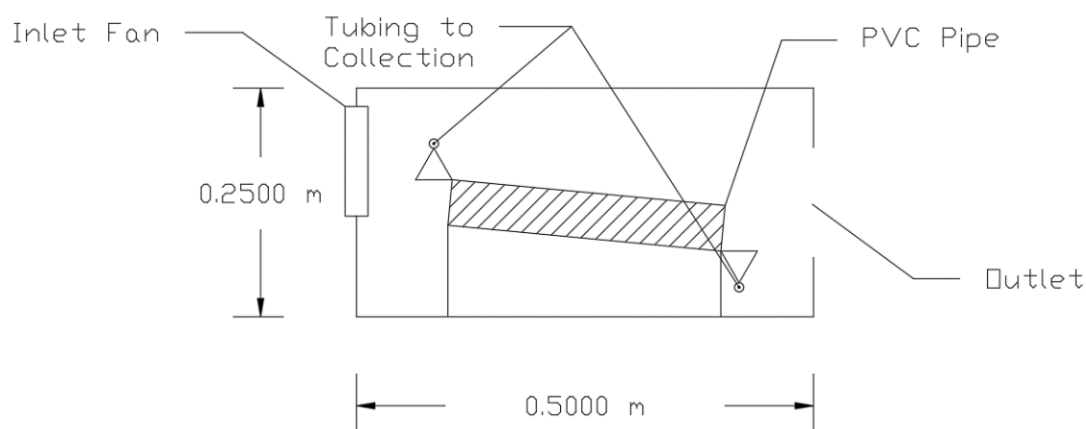


Figure 7 - CAD diagram of device interior configuration. This demonstrates the locations of all interior components, as motivated by COMSOL models. Water released by the sorbent materials will be funneled into tubing, which then will direct it to the final collection point on the device's exterior.

4.5. Electrical Components

The design of electrical components in the device is very important to ensure that it can operate successfully in the absence of any external power source. While some power needs have been replaced with sources other than electricity, such as by using the sun as a heat source, this is less feasible for other components. Specifically, sensors tracking the humidity and temperature around the device and the fan drawing air in require electrical power to run. This section will describe how these components have been designed to still meet the technical goals of this project.

4.5.1. Humidity & Temperature Sensors

Although sensors monitoring relative humidity and temperature do not directly influence the performance of the device, they are crucial facilitators of data collection to ensure that this project meets the technical specifications. An exterior sensor, located immediately adjacent to the inlet fan so as to measure the characteristics of incoming air, will constantly monitor RH and temperature during the absorption cycle. This will ensure that the air from which water is absorbed during any experimental trials is at or below 40% relative humidity, and therefore is accurately representing the arid conditions for which this device is targeted. Similarly, an interior sensor, located on the floor in the center of the box, will monitor the interior temperatures during the desorption cycle to make sure that the thermal absorber is creating the necessary temperatures for water to be released. By collecting this data throughout all trials, it can be confirmed whether or not these technical specifications have been met.

After discussions with some of the electrical engineering advisors from the Active Learning Labs, DHT22 temperature and relative humidity sensors were selected for this purpose [42]. These sensors were already available in the lab for student use and are also relatively inexpensive should more ever need to be purchased. Additionally, since each one can measure relative humidity and temperature simultaneously, only two sensors are needed to measure these values for the device interior and exterior rather than four. These sensors are capable of taking measurements every two seconds, an interval that is more than frequent enough to monitor the environmental conditions for the purposes of this project [42]. In order to power these sensors and collect the data that they are measuring, a circuit was set up on small breadboards connecting the sensors to an Arduino MKR Zero microcontroller [43]. Each sensor has three pins: one positive, one negative, and one which carries the data signals. Along with a few resistors, these all eventually connect to the microcontroller, which connects through a USB port to a computer for power. This also allows the data being collected to display on that computer during operation for recording purposes. Code written in Arduino controls the collection and display of temperature and humidity data. This was largely taken from examples on the Adafruit website, with slight modifications to fit this project's needs [44]. Complete code can be found in Appendix 4 (section 10.4). It was also initially intended that data would be saved to a SD card using this code, but due to several difficulties it was decided that temperature and humidity data will be manually recorded at frequent intervals during experimental trials instead. The general setup of the sensor circuitry can be seen in Figure 8 below. The only difference between this and the final circuit is that the wires were eventually lengthened so that the sensors could be located farther apart on the interior and exterior of the device.

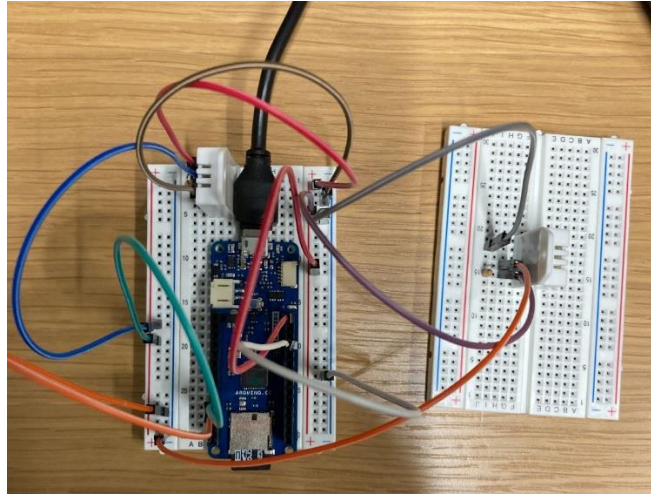


Figure 8 - Sensor circuitry. Pictured are 2 DHT22 Relative Humidity and Temperature sensors along with an Arduino MKR Zero microcontroller. This is an initial setup before sensors were integrated with the entire device.

4.5.2. Solar Panel & Battery

It was originally planned that a solar panel and battery setup would be used to power the inlet fan. By charging the battery during the daytime and then using it to run the fan during the absorption cycle, this would help to achieve the goal of operation independent of any external power source such as a grid. The battery would likely have been connected into the same microcontroller unit as the sensors, which could then be coded to determine when it was turned on to operate the fan. However, due to time limits there was not an opportunity during this project to fully design these elements of the system. For this reason, the fan will be powered by a wall outlet using a 3-pin to USB adapter cable. While unfortunately this configuration does not entirely meet the stated energy goals for this project, it would not significantly alter any other design aspects if this power source was later converted to a solar panel and battery system. Therefore, with a little more time it would be feasible to meet this goal. This makes the solar panel and battery setup a definite area for future improvement in the design of this device.

5. Device Build

There will be a few broad steps to complete during the build process of this project. First, independent of the device itself, a method for controlling humidity for experimental trials must be assembled. This is important to ensure that the relative humidity can be set below 40% to accurately represent the targeted arid regions. To construct the device itself, the first step will be to assemble the exterior walls and the components of the solar thermal absorber. Initial verification tests of these elements will then be conducted as described in the Measure & Verify section, and finally the interior components to hold the sorbents and collect water during desorption will be added.

5.1. Experimental Humidity Control

As has been previously stated, having the ability to control ambient humidity during experimental trials is crucial to determining the success of this project. Without being able to create low humidity conditions in the lab setting, there would be no way to confirm whether or not the device can successfully operate in arid environments around the world. In order to achieve this, several methods were initially considered. One option was to use an environmental chamber in a lab on campus, but logistics of access and scheduling proved difficult. Another option was to use a dehumidifier, such as one commonly used in homes, to reduce the humidity with sensors monitoring in an enclosed space such as a small room. However, dehumidifiers that are both commercially available and within a reasonable price range for this purpose generally did not have the capability to generate RV conditions below 40%. On average, their lower bounds were in the range of 40% to 50% [45]. In hindsight this makes sense, since a humidifier that could reach even lower values would essentially also be a device that could generate water in those conditions, essentially defeating the purpose of this project.

Based on all of this, the ultimate decision was to use a small space heater within an enclosed space to control humidity. As a rule of thumb, air within an enclosed space will experience a decrease in relative humidity of about 6% for every degree Celsius increase in temperature. If we take the average humidity in Cambridge, MA of about 60% to 65%, this means that the space would only need to be warmed by approximately 4 to 8 degrees to reach the target RH values [32]. Throughout any of these experiments, the DHT22 sensor on the device's exterior would be constantly monitoring humidity as described above, allowing continuous verification that operation is occurring within the desired range. Compared to other options considered, this method was easily accessible, inexpensive, and can achieve the desired RH values, making it the best choice.

One unforeseen solution that also arose is that the Environmental space in the SEAS Active Learning Labs where this project was primarily conducted has an average RH of approximately 20% to 30%. This was realized when some initial testing of the temperatures inside the solar thermal absorber was conducted, and over relatively long periods on multiple days the RH measured by the sensors remained below 40% naturally in the room. While it is impossible to guarantee this will always be the case, it may be feasible to conduct experimental trials without a humidity control setup. However, the space heater will still be present as an option to turn on near the device's inlet should the sensors ever indicate that RH is rising to a more humid value.

5.2. Material Selection

Another very important step in the build process of this device was to select appropriate materials for each of the components. Sorbent material selection has already been explained in detail within the Design section, but besides that there were still several other components for which choices needed to be made. While selected materials must be able to adequately perform their individual functions in helping capture drinking water, two other important factors in this decision-making process were cost and commercial availability. If a material were too expensive and difficult to source, it would present difficulties both within the scope and budget of this project and also for the desired end users. Especially with sorbent materials already comprising a fairly significant cost that would need to be replenished every so often, cost of the remaining materials was of very high importance.

One component for which a material needed to be chosen was the exterior walls of the device. While these play little role in actually absorbing and desorbing the water, they must be sturdy and have an ability to protect the interior components from general wear that they might be exposed to in a variety of environments. For these reasons, a hard acrylic plastic material of $\frac{1}{4}$ " thickness was selected. This type of plastic is sturdy and was readily available for use in the Active Learning Labs. It would also be relatively inexpensive if the device is ever produced on a larger scale. Finally, acrylic plastic can experience temperatures of up to approximately 160 degrees C before melting, meaning there should be no issues with the temperatures that the interior is expected to reach [46].

Another few choices needed to be made for the materials that would make up the solar thermal absorber. To start, a thin aluminum sheet was chosen to serve as the top layer of the absorber [47]. This sheet at dimensions of 1 foot by 2 feet is large enough that the entire top of the device can be cut out as one piece, and thin enough at 0.19 inches thick that machines available in the Active Learning Labs will be able to cut through it. A metal was selected since it will conduct heat well, therefore helping to maximize the temperature increase within the device. Additionally, a flat black protective enamel paint was selected to apply to the top of this metal sheet [48]. This will reduce reflectivity of the metal and increase the percentage of incoming solar radiation it is able to absorb, therefore additionally increasing the maximum possible interior temperatures. It should also provide some small level of additional protection to the aluminum material. Finally, a bubble aluminum foil reflective thermal insulator material was selected to line the interior of the device [49]. This material is inexpensive, provides no contamination risks to the sorbent materials or water, and is highly thermally reflective. By lining and taping this along all of the interior walls, it should help reduce heat losses during the desorption cycle and therefore maintain higher temperatures within the box.

Finally, a few other material decisions needed to be made for components on the interior of the device. PVC piping and plastic tubing were selected to hold the sorbent materials and direct desorbed water respectively. These are very common materials that likely would be accessible almost anywhere in the world, and a brief search determined that the temperatures within the device would not cause any issues for them [50]. A couple small plastic funnels will be used for similar reasons, and the final collection point for water on the device's exterior will be something such as a beaker available in the lab. In a real-world application, this final collection container could really be any type of bucket, jug, bottle, or other type of container that the end user preferred to store drinking water in.

5.3. Device Exterior & Solar Thermal Absorber

In order to begin the build process of the device, the first step was to assemble the exterior walls out of the acrylic plastic. After discussions with Active Learning Labs staff, it was determined that using the laser cutter would be the most efficient and precise method of completing this. This allowed very accurate dimensions on all the pieces that were cut and could be completed within a period of less than an hour. In order to use this machine however, a representation of the device with accurate dimensions needed to be created in a CAD software so that it could be input to the laser cutter. This representation is shown in Figure 9 below, including the bottom of the device, four side walls, openings for the inlet fan and the outlet at the back of the device, and holes where screws will be located to hold the walls together. These holes were based on No. 9 size screws, since these would fit with brackets that were available in the Active Learning Labs [51]. The box has a height and width of 0.25 m and a length of 0.5 m. These dimensions were chosen to create a medium sized device that could fit the interior components without being unnecessarily large and cumbersome for end users. Having this CAD drawing, the five sides could then be cut out and connected together with screws through the wall and brackets held internally by nuts. In total, 16 brackets and 32 screws were used.

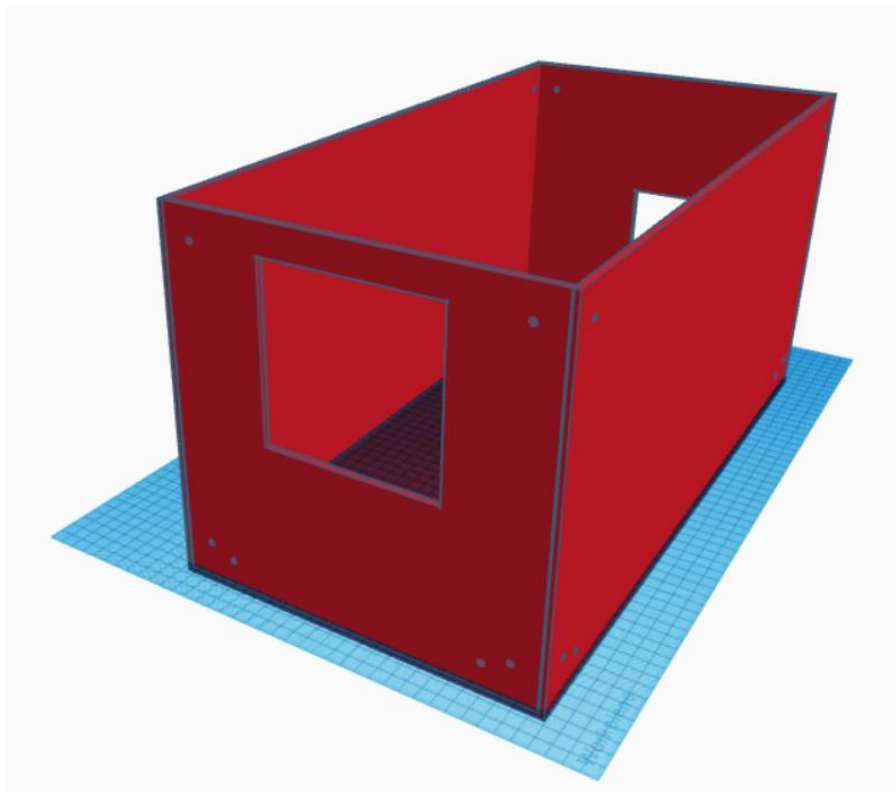


Figure 9 - CAD representation of device exterior walls. These were generated with accurate dimensions so that the laser cutter could take them as an input and produce the walls from larger acrylic plastic sheets. Each marking on the grid represents a distance of 1 cm.

After this, the next step was to implement the solar thermal absorber. This involved two primary components, the aluminum sheet to serve as the device top and the insulating material to line the interior walls. It was determined that the aluminum sheet would sit on the interior wall

brackets, allowing it to serve as the device's lid while remaining removable so that users can access the interior components as necessary. To cut the correct dimensions of 0.25 m by 0.5 m out of the larger 1' by 2' sheet, a metal shear in the Active Learning Labs was used. However, this shear could not fit any piece with a width greater than 1'. This means that the sheet would not fit in the long orientation, and instead two separate pieces were cut. Each has dimensions of 0.25 m by 0.255 m, so that they could be overlapped slightly and connected into one sheet of the appropriate size. Duct tape was used to connect these two smaller sheets, and tape was also folded around all edges of the sheets to cover any burrs that may have been created during the shearing process for user safety. Afterwards, one entire side was painted black to reduce reflectivity as previously described. This was just done by hand using a small brush and will serve as the side facing up on top of the device.

As this was left to dry overnight, the insulation was added along all interior walls. This was done by cutting pieces out from the larger roll of material for each of the four sides and the bottom, leaving holes for things such as the inlet and outlet. Initially, these were all secured using duct tape between the back side of the insulation and the inside of the walls. After some initial temperature testing however, additional tape was added along all edges on the interior side of the insulating material to further prevent heat losses. The device following this build stage, including the exterior walls and both elements of the solar thermal absorber, can be seen below in Figure 10.



Figure 10 - Built Device Exterior Structure. Exterior hard plastic walls have been assembled, along with the solar thermal absorber including insulation and black aluminum sheet. At this stage, the interior components are not yet present.

5.4. Interior Components

The final components of the device to be assembled were the interior parts that will hold the sorbent materials and allow water to be collected once it is desorbed. To begin, the 2" diameter PVC pipe holding the sorbents must be suspended in a way that allows air to flow through it during the absorption cycle, can be connected to funnels for water collection during

the desorption cycle, and is removable so that users can easily add and remove sorbent materials over time. The pipe must also have small ridges along its interior so that the sorbent materials do not just slide out of the lower end when it is placed at a slant. To achieve this, it was determined that the pipe would rest on top of two bars crossing the device, with the one near the rear of the device being slightly lower to aid in water collection. These bars were made of cardboard taped on both ends, with rolled up pieces of cardboard located underneath, acting as columns to provide additional support. Cardboard was selected primarily due to its immediate availability and low cost, although if this device were reproduced more robust materials would likely be a better choice for long term durability. Small bumps made of cardboard were also added on top of the bars to prevent the pipe from rolling to either side during operation, and the edge of the cardboard on the lower bar was folded upwards to prevent the pipe from sliding backwards. With this structure the pipe should be able to rest suspended throughout the absorption and desorption cycles but can also be lifted out as necessary. This can be seen in Figure 12 at the end of this section.

The other important element of the build process involving the pipe was adding ridges along the interior bottom to hold the sorbent materials in place. To do this, four small pieces of cardboard were cut out so that they would rise approximately 0.5" from the lowest point of the pipe. These were then placed in four locations along the interior of the pipe and attached using hot glue and tape. Pliers were used to reach further inside in an attempt to space the four ridges as evenly as possible, although the gap between the two central ones is slightly larger. With these structures in place, a spatula available in the lab was used to place sorbent materials into each of the sections for experimental trials. In each instance, the goal was to maximize the surface area of the sorbent materials by spreading them out as evenly as possible. This allows maximum interaction with air, and therefore the greatest rates of absorption. Figure 11 below shows an image looking down the pipe with the ridges and some Zeolite 3A that has been added. The pipe was slightly rotated in error while lifting to take the image, so the sorbents in the foreground of the image do not have the maximum surface area as they would during device operation.



Figure 11 – Image of PVC pipe interior, showing several ridges along the length to hold sorbents in place while pipe is sloped. Zeolite 3A has been added to the pipe in this image, although due to a slight rotation while taking the image, some of the material has moved slightly. It would be spread out more to maximize surface area for absorption during operation of the device.

Once this construction of the pipe was finished, the device was essentially ready to be run through absorption cycles. The final brief step of the assembly would just be to add the fan to the inlet. Since the inlet hole was laser cut to the correct size for the fan, it can just slide in and rest in the proper position. To power this fan, its 3-pin connection needed to receive power somehow. While the original plan was to connect this into the microcontroller with the RH and temperature sensors, it proved easier to purchase a 3-pin to USB adapter cable. This could then be plugged directly into a computer or outlet to run the fan. This makes no real difference for the device, as either way the fan is being powered by an external electrical source.

With the components that have been described so far, the device could successfully operate an absorption cycle as designed. However, the interior configuration requires a few additional components to collect the water during the desorption cycle. Since the water is primarily released from the sorbents as a vapor, they need to be enclosed within the pipe to prevent losses back to the ambient air. This is where the funnels and tubing come in, with the funnels placed as tightly as possible at the end of the PVC pipe and then leading into the tubing to the outside of the device. This connection was originally made with duct tape, but later with a Velcro tape that was available in the Active Learning Labs. This switch was made for two reasons: the tape did not seem to hold up as well within the high temperatures of the desorption cycle and the Velcro tape made it easier to place and remove the funnels between the two cycles. For the purposes of this project changes between the absorption and desorption cycles, which primarily involved putting the funnels and connected tubing into place, were done manually. However, making this automated in the future would certainly make operation much simpler for end users.

The plastic tubing connected to these funnels was then run out through the inlet and outlet holes at each end of the device. For the desorption cycle, the fan is removed and additional sheets of insulation with holes for the tubing are placed in the inlet and outlet to aid in preventing heat loss. At the beginning the tubing from both ends was curved around into one combined final collection point, but after some initial testing this was changed to having shorter pieces of tubing that went to separate beakers at the front and back. The reason for this is described in the verification section, although observations showed that all water eventually collected came from the tube connected to the higher end of the PVC in either case. These final collection sites were just beakers from the lab space that the tubing would drip water into, making it very easy for users to access. If this device were to be used in a real application, a useful addition might also be some removable cover for the beaker that the tubing goes through to prevent any evaporative losses over long cycles.

With these components all in place, the device is now able to hold sorbents to absorb water and collect that water once it is released. Besides these, there are just a couple other minor components located within the box. First, one of the two sensors as described in the Design section is located within the device. It is configured exactly as shown in Figure 8, just with longer wires to allow one sensor on the interior and one on the exterior. These wires were run through the outlet of the device. Finally, as will be described in the verification section, a hot plate was ultimately used as a heat source in trials of the device. This sat on the floor of the device underneath the PVC pipe, and a wire to power it also ran through the device outlet. All of these interior components together can be seen below in Figure 12.



Figure 12 - Image of device interior components as initially assembled. This includes the suspended PVC pipe to hold sorbent materials, funnels and tubing to collect water during the desorption cycle, the exterior final collection site, a sensor, and a hot plate. Some minor changes were later made to this build based on test results, such as changing tape connections to Velcro tape and switching from one collection site to two.

6. Analysis and Verification

Throughout stages of the build process, and most importantly at the end once the whole device had been assembled, several experiments were conducted to analyze and verify the performance in relation to the technical specifications. This section describes the methods, results, and impacts of these various experiments.

6.1. Individual Component Verification Experiments

As has been briefly mentioned already, certain components of the device were tested before being incorporated into the complete device. This serves a variety of purposes, such as verification of rated specifications or collection of data that may influence later design and build steps. For this project, these types of tests were carried out for several primary components of the device: the chosen sorbent materials, the solar thermal absorber, and the interior water collection mechanism.

6.1.1. Sorbent Material Tests

The first characteristic of the chosen sorbent materials that was tested was their absorption capacity. This is very important to determine how much water the sorbent material can hold, and therefore ultimately how much water the device might be able to provide. In order to analyze this, known amounts of each dry sorbent were measured by mass. These were then spread out on small trays to maximize the surface area exposed to air and were left to sit overnight to absorb water. This was done without any external humidity control, since as previously stated the RH in the lab room was observed to stay around 20% to 30% on average. This means that without any control it was already within the desired arid range. There was no fan blowing air onto the materials, and instead they just absorbed from the air passively. While this is slightly different from how the device will operate, it should only change the speed with which absorption occurs and not the water capacity.

After a day of being allowed to absorb water, the masses of each material were measured again using a scale. This is a sufficiently long time to where the materials should be near their maximum in terms of absorbed water. Each material had increased in mass, and therefore the total amount of water it had absorbed could be determined by subtracting the initial mass from the final. In other words, the added mass represents the mass of water being held by the sorbent. Therefore, in order to calculate the absorption capacity of the material, the amount of water could just be divided by the initial dry sorbent mass in order to find a value of mass water per mass sorbent material. Three trials of this experiment were carried out for each of the two materials, and the results are shown below in Table 5. Figure 13 below also includes microscope images taken during these trials, showing an example of how the materials change once they have absorbed water.

Table 5 - Sorbent Material Absorption Capacities

Material	Trial	Initial Sorbent Mass (g)	Mass Water Absorbed (g)	Absorption Capacity (g water/g sorbent)
Zeolite 3A	1	25.006	5.131	0.205
	2	25.001	4.621	0.185
	3	25.000	4.643	0.186
			Zeolite 3A Average	0.192
Silica Gel	1	10.005	0.381	0.038
	2	10.000	0.203	0.020
	3	10.001	0.194	0.019
			Silica Gel Average	0.026

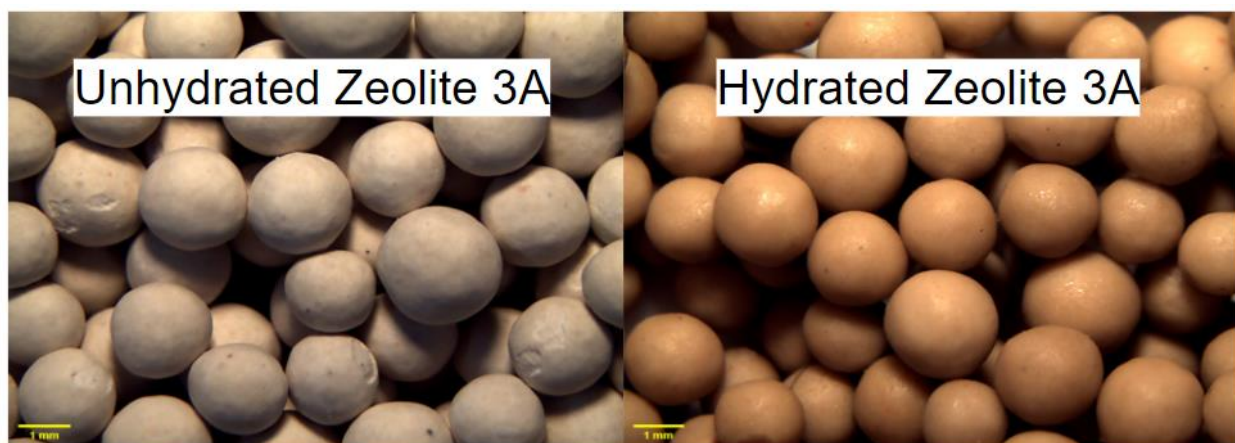


Figure 13 - Microscopic images showing a sample of Zeolite 3A before and after hydration. This demonstrates an example of how the sorbent materials change once they have tightly bound the water that they absorb.

The other important characteristic of the sorbent materials to be tested was their desorption temperature, or the temperature at which the previously absorbed water is released. In order to test this, the materials that had previously collected water during absorption experiments were placed in glass beakers in a laboratory oven. At this point, the total mass and the mass of water was known for each trial based on the absorption experiments. Starting at a temperature of 60 C, the oven was then increased by 10-degree intervals. At each temperature, the materials were allowed to sit in the oven for approximately five minutes, then their mass was measured. As temperatures increased, the overall mass was expected to decrease, corresponding to water that was being released out of the system. Therefore, by tracking at what points greater amounts of water were released, it would be possible to determine the optimal desorption temperatures for each material. Three trials of this were conducted for the Zeolite 3A, and two trials gathered complete results for the silica gel due to an experimental error. Results for the mass of water absorbed to the materials versus temperature are shown below in Figure 14.

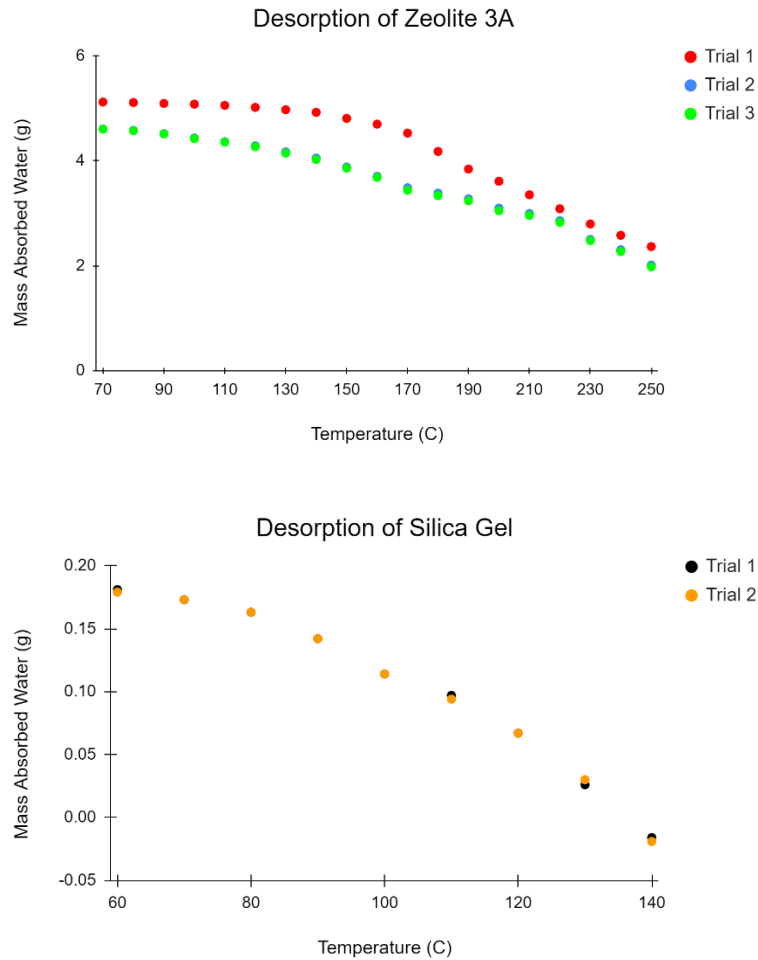


Figure 14 - Results of sorbent material desorption experiments. The curves represent mass of water still absorbed to the materials versus the temperature they have been heated to. The points where the slopes begin to increase in magnitude correspond to the observed desorption temperatures of each material. The top graph is for the Zeolite 3A material, while the lower graph is for the silica gel.

From the above results, we can determine the optimal desorption temperatures by looking for the points where the masses of absorbed water begin to decrease more rapidly for each material. For the zeolite this is around the range of 150 C to 175 C, and for the silica gel it is around 90 C to 100 C. Both of these values generally match the expected desorption values as determined from previous literature.

More importantly, these desorption temperature results along with the absorption capacity experiments further emphasize the fact that there is a distinct tradeoff between these two characteristics for each material. The zeolite can hold significantly more water but needs to reach a much higher temperature to release it, and vice versa for the silica gel. This further confirms that neither material independently will likely be optimal for this device, but hopefully can together simulate the performance of a material such as a MOF.

After determining the desorption temperatures above, it became evident that the times associated with desorption would also be important to consider. Although the previous data gave a good understanding of the optimal temperatures at which each material would release absorbed water, the rate at which the water is released will also be important for determining the amounts of water that can be produced over the time of each desorption cycle. In order to determine this, a similar experiment was conducted where known masses of each sorbent material along with known masses of absorbed water were placed into the laboratory oven. However, this time the oven remained at a constant temperature of 100 C, the goal temperature for the device interior during the desorption cycle, and mass measurements were taken at constant time intervals every three minutes. It was then similarly possible to determine the amount of water left absorbed to the materials at each time, and therefore determine trends for how long the desorption processes were taking.

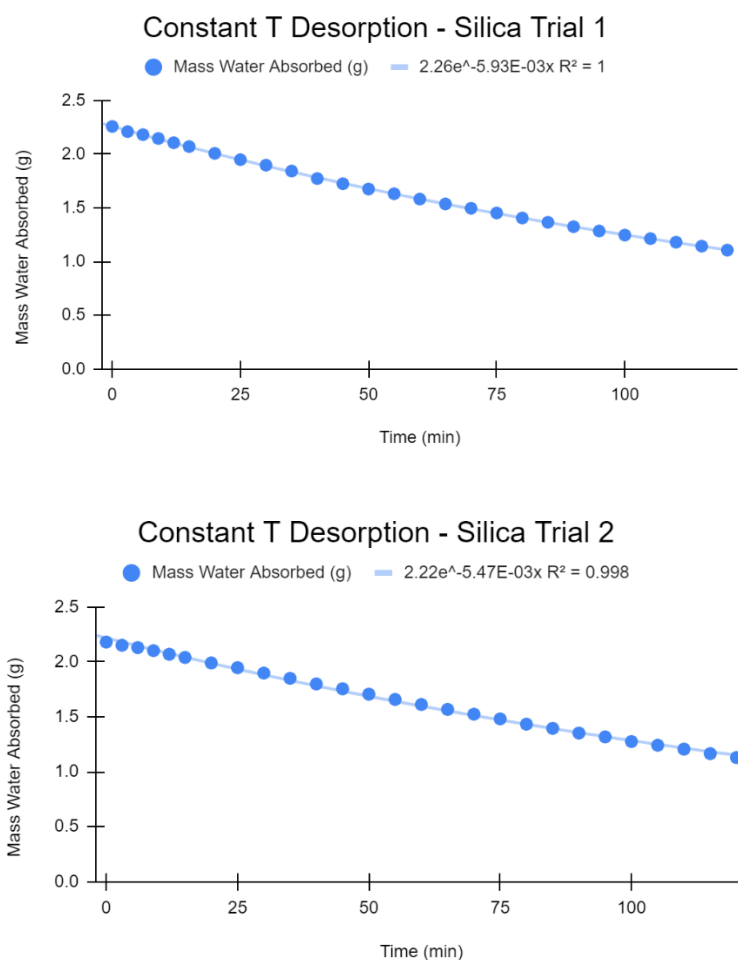


Figure 15 - Constant temperature desorption experiment results for silica gel. The graphs represent the amounts of water left absorbed to the material over time for two trials, along with exponential decay curves which fit the measured data very well. These two trials have an average e-folding time of slightly over five hours.

Shown above in Figure 15 are the results of the two trials of this experiment conducted for the silica gel. Exponential decay curves fit this data very well, with R^2 values of 1 and 0.998

respectively for each of the two trials. Complete fit equations can be found in the figures above. This exponential trend is as expected, as the material will desorb at a slower rate over time when it has less and less water. From these trials, the silica gel material was found to have an e-folding time of approximately 317 minutes. This time corresponds to the amount of time it takes the amount of water absorbed to the silica to reduce to $1/e$ times its original value and was found by simply setting the best fit equations equal to $1/e$ times the known original value and solving for time. This time of a little over five hours to release a majority of the water is very reasonable, since it is expected that an average desorption cycle will be approximately eight hours. An identical experiment was also run using the Zeolite 3A sorbent material, and the results are included below in Figure 16.

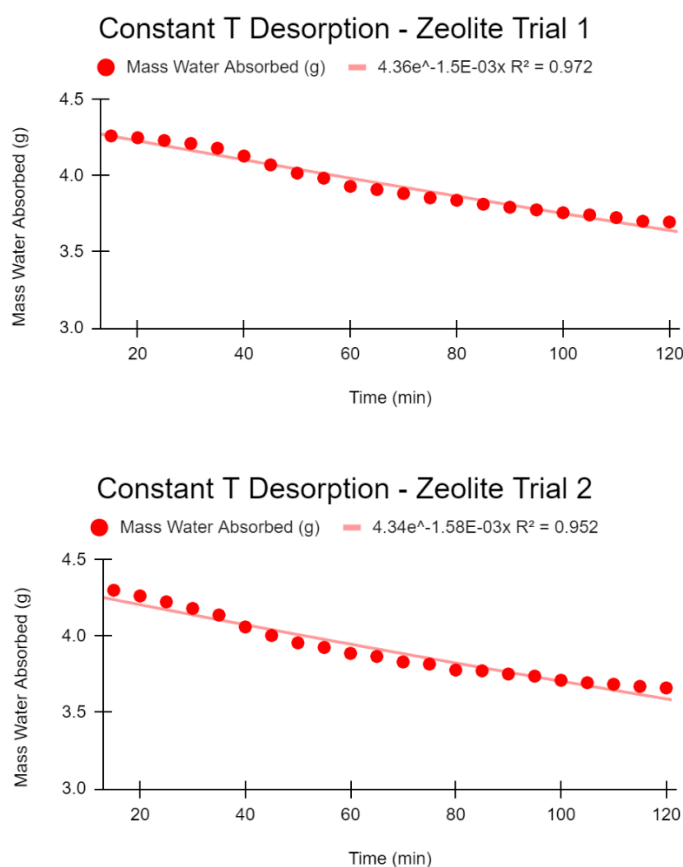


Figure 16 - Constant temperature desorption experiment results for Zeolite 3A. The graphs represent the amounts of water left absorbed to the material over time for two trials, although several outlier data points were removed at early time points. Exponential decay curves fit the remaining measured data relatively well. These two trials have an average e-folding time of over 24 hours.

Although not as close as for the silica gel, exponential decay curves still fit this data for the zeolite relatively well with R^2 values of 0.972 and 0.952 for the two trials respectively. The complete fit equations can be found in the figures. It is important to note that several data points at early times were removed, as the rate of water removal was extremely quick. This is likely water that was not bound to the zeolite evaporating away early on rather than water that was actually absorbed being released, and for this reason these data points were ignored. e-folding

times were calculated using the same procedure as for the silica gel, and the average over both trials was greater than 24 hours. This is significantly longer than for the silica and would likely result in a lot of water still absorbed to the zeolite after a full eight-hour desorption cycle. However, this result was expected since the oven was only set at 100 C. At higher temperatures the zeolite would likely release water much more quickly, but the fact that these trials were at lower temperatures explains the slow desorption rates observed. This shows that the zeolite likely will not function optimally at the temperatures this device is designed to reach, although it still may be able to generate some small amounts of water.

6.1.2. Solar Thermal Absorber Tests

Similar to the sorbent materials, the solar thermal absorber was also analyzed before the rest of the interior components were added to the device. This is a fairly straightforward experiment, with the device being exposed to solar level radiation from the top with sensors on the interior monitoring the temperature increase over time. For the first two trials, the light source used was a small heat lamp borrowed from Glen Andrew de Vera from the Active Learning Labs. In each case, there was not a set time for which the temperature was tracked, but instead measurements were taken every two minutes until the temperature had leveled off or started decreasing. The results from these two trials can be seen in Figure 17 below. For Trial 1 the ambient temperature as given by the room's thermostat was 21.1 C and for Trial 2 it was 20.3 C.

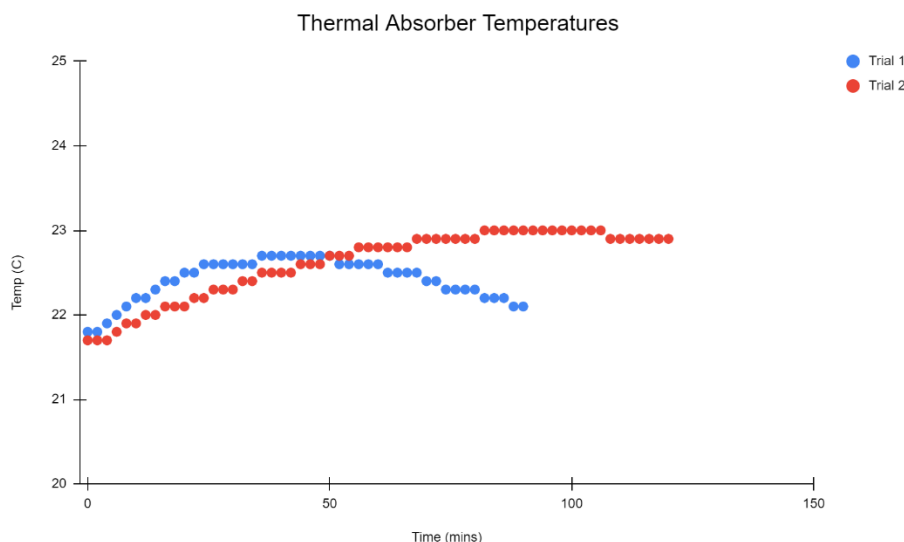


Figure 17 - Results of solar thermal absorber verification experiments. The curves represent the temperature within the device versus time elapsed under exposure to solar level radiation.

Based on this, the device was only able to reach temperatures of about 23 C.

These results were clearly not anywhere close to the temperatures required to significantly desorb either of the sorbent materials. Some changes were made between the two trials, such as adding tape along all interior edges to help insulation and adding a piece of insulation over the fan, but the resulting temperature increases were minimal. The other primary reason why it is expected that this was unsuccessful is that the lamp was not accurately

representative of the solar spectrum. The light source that was used in these trials was a 12W LED bulb, and it was shined on an area of roughly 0.0625 m². This corresponds to an incoming power of about 192 W/m² at the top of the device, which is less than 20% of the standard solar intensity value of 1000 W/m² on earth's surface [52]. Additionally, it is likely that the emission spectrum of this LED lamp is not exactly the same as that of the sun, which covers a wide range of wavelengths. For both of these reasons, the lamp used was likely not an adequate representation of actual incoming solar radiation.

Based on this conclusion, a few other options were considered for simulating the sun and providing heat during the device's desorption cycle. First, devices made specifically for the purpose of simulating solar level radiation in a laboratory setting were considered, but these 'solar simulators' cost several thousand dollars minimum and therefore were not feasible within this project's budget [53]. Other types of lamps were also considered, such as xenon lamps which are said to match the solar spectrum relatively well [54]. However, these were also too costly [54]. For all of these reasons, the decision was made to use an electric heat source for device simulations. Although this violates one of the goals of this project, being able to achieve the desired temperatures within the device will prove that the other components all function as designed. Additionally, the solar thermal absorber as designed would theoretically reach higher temperatures than shown if exposed to actual solar radiation. Improved testing and design iterations of this system to obtain higher interior temperatures would certainly be an area of further research interest. After testing two electric heat sources, a space heater and a hot plate from the laboratory, the hot plate was ultimately selected for this purpose based on the rate of temperature increase and the maximum temperatures it was able to achieve within the device. These results are shown below in Figure 18.

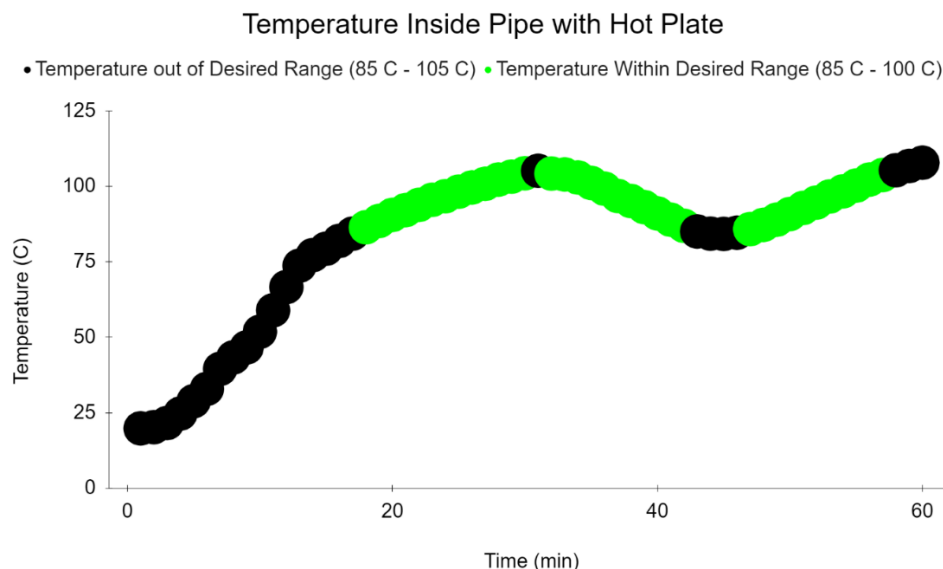


Figure 18 - Temperatures inside of sorbent material pipe with hot plate as heat source. This chart shows the temperature over time as measured by a thermocouple placed inside of the PVC pipe where sorbent materials will be held after a hot plate located on the device's floor has been turned on. Green data points are within the target range of 85C – 105C, while black points are outside of this range. The temperature oscillates at later time points due to the hot plate being turned on and off in an attempt to stay within this target range.

As can be seen above, the hot plate reaches the desired range of desorption temperatures in approximately 20 minutes. In the figure, data points within the desired temperature range of 85C – 100C are shown in green. This is very short compared to the several hours that the desorption cycle will run to collect all of the water, and therefore this process should reach the necessary temperatures effectively. These measurements were taken using a thermocouple placed inside of the PVC pipe, importantly showing that this piping will not prevent the higher temperatures from reaching the interior where the sorbent materials will be located. The hot plate was set to a relatively high setting of around 400C to reach these temperatures in a reasonable time, which did cause a small issue with the section of the pipe nearest to the plate beginning to deform slightly. However, this was solved by placing an additional layer of the thermal insulation material from the walls on the bottom of the pipe between it and the hot plate, preventing such direct heating at very high temperatures. In another trial the pipe interior still reached the desired temperatures around 90C with this addition, although the process did take closer to 50 minutes. However, this is still relatively short compared to the overall length of the cycle and should not be an issue.

6.2. Water Collection Mechanism Verification

The final individual component to be verified within the device was the water collection mechanism during the desorption cycle. The purpose of this experiment was to ensure that the system of funnels and tubing would be able to actually gather water and direct it to the final collection site during the desorption cycle. In order to do this, known amounts of water were added to known amounts of the silica gel material and then loaded into the PVC pipe using a spatula. A desorption cycle was then run for two and a half hours based on time available, with the hot plate providing heat and the entire collection mechanism in place. The volume of water that ultimately reached the final collection point was then measured and compared to the initial amount of water added to the sorbent. Two trials of this experiment were run, and the results are shown in Table 6 below.

Table 6 - Water Collection Mechanism Verification Results

Trial	Mass Silica Gel (g)	Mass Water Added (g)	Volume Water Collected (mL)	% Water Collected
1	14.999	5	0.15	3%
2	15	8	0.4	5%
			Average	4%

These results show that some small amounts of the water from the sorbent materials were captured by the water collection mechanism and ultimately directed to the final collection sites. The volumes collected are approximations, as it would be difficult to precisely measure the volume of small water droplets. Instead, the common approximation was used that each drop of water is 0.05 mL [55]. Then, using the fact that water has a density of 1 gram per milliliter, it was possible to calculate the percentage of water ultimately collected out of that initially added to the silica gel sample. Over the two trials, this came out to an average of 4% of the total water reaching the final collection point.

One immediate takeaway from these results is that more water certainly would be collected over a longer desorption cycle. These results were from a 2.5-hour cycle, but a simple linear projection to a full 8-hour cycle projects that about 12.8% of the initial water would be collected. There are certainly other factors that could impact this value, and as shown earlier the desorption rate would likely slow down over time, but certainly more than 3-5% of the water would be collected over a significantly longer trial.

Besides the time component, several other small iterations were made to the device based on observations made during these trials. First, the PVC pipe was initially connected to the funnels using duct tape, but this was observed to have stretched out over long periods at the high temperatures inside of the device. This led to small gaps at the connection between the funnel and pipe, where some vapor certainly could have escaped back out into the surrounding air. In order to fix this, a Velcro material available in the lab was instead used to fasten the two components together. This was still easily removable for the absorption cycle, but by observation in later experiments seemed to hold up a little better at high temperature. However, this connection between the PVC and funnel is still certainly a location where some loss of water is likely, and therefore is an area that could use more development in the future. Another change was the switch from one joint collection site to two separate beakers at each end of the device after the first trial. It was observed that water was condensing in the tubing almost immediately after exiting the device, and this change allowed the tubing to be at a much greater slope. This allows gravity to act on this water much more quickly so that it will reach the final collection site sooner. Through many trials it was ultimately observed that all water collected came at the front of the device (the side with the higher end of the PVC pipe) since the water was being released from the sorbents in the gaseous state, but the second collection site was kept just in case. The final small build iteration after these trials was the addition of a piece of insulation on the bottom of the PVC pipe between it and the hot plate. It had been observed that the section of the pipe closest to the heat source was beginning to deform slightly after several hours at high temperatures, and this insulation was a preventative measure to ensure that this did not become a larger issue during later trials.

6.3. Overall Device Testing and Results

6.3.1. Procedure

Once the build procedures have been entirely completed, tests of the overall device will be ready to begin. For these experiments, the device will be run through entire absorption and desorption cycles to resemble how it might operate in the real world as closely as possible. At least three trials, with each containing an absorption cycle and desorption cycle, will be conducted in settings where the humidity is below 40%. During the desorption cycle, the original plan was to use a lamp to simulate solar radiation. However, as explained above, after initial verification experiments it was determined that a hot plate would be used as the heat source in order to verify the rest of the device within the correct temperature ranges. Within one trial, the absorption and desorption cycles will each be run for three hours. This six-hour total cycle is likely shorter than what would likely be run in reality due to time constraints, although the results can be projected out for longer cycles of operation. Throughout each trial, several values will be measured to evaluate the performance of the device relative to the technical specifications. The methods and results for each of these are described in the following sections.

6.3.2. Humidity and Temperature Measurements

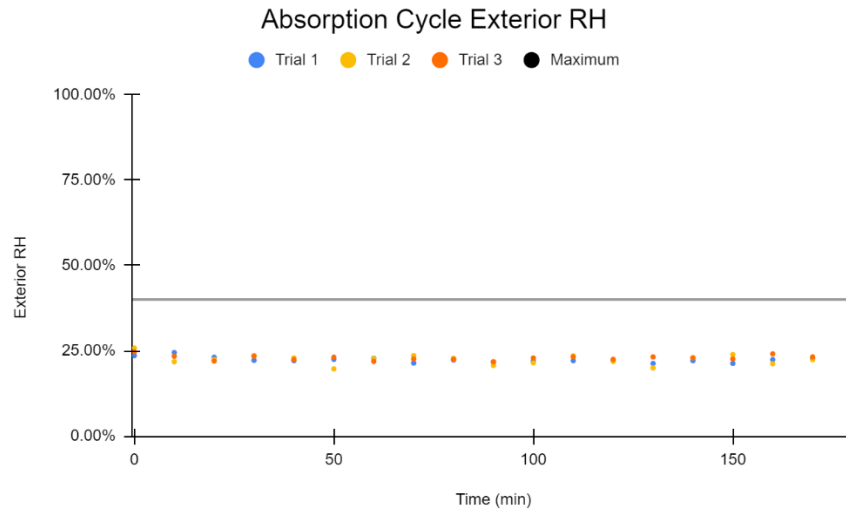


Figure 19 - Absorption cycle external RH measurements from each trial of the completed device, as measured by a DHT22 sensor. The humidity throughout all three trials remained well below the 40% threshold, meaning that the device was operating in conditions representative of arid regions. Any water collected in these trials therefore was absorbed out of arid air.

The above results in Figure 19 show the relative humidity values outside of the device throughout each absorption cycle of the device. These values were gathered by a DHT22 sensor placed adjacent to the inlet, therefore measuring the humidity of the air that the fan was drawing into the device throughout each cycle. Over all three trials, which occurred on three separate days, the RH remained relatively consistent around 25%, and was always significantly below the maximum of 40%. This means that the air being drawn into the device during each absorption cycle trial was within the necessary range, and appropriately represented the conditions that would be present in arid regions of the world. Therefore, any water ultimately produced by these trials would be coming from arid air. This operating condition goal for the device was certainly met.

Similarly, sensors were also used to track the interior temperatures of the device throughout the desorption cycle of each trial. In each case the trend over time was essentially the same as is shown in Figure 18. The device would reach the desired temperature range within 20-30 minutes, and then would oscillate for the rest of the cycle as the hot plate was turned on and off to maintain a temperature within this range. With the hot plate as the heat source, the device had no issue reaching the desired temperatures to be able to desorb the sorbent materials.

6.3.3. Water Volumes

Another important metric of success is the volumes of water that the device is able to produce. For the purposes of this project, water produced is any liquid water that has reached the exterior final collection site by the end of the desorption cycle of a trial. It was initially

planned that a graduated cylinder would be used to measure the water after each trial, however at small volumes this would have given a very imprecise measurement. Instead, each droplet of water collected from a trial was considered to be 0.05 mL [55]. Results for two trials using the silica gel are shown in Table 7 below.

Table 7 – Silica Gel Water Volumes Collected

Trial	Mass Silica in Device (g)	Volume Water Collected (mL)
1	14.999	0.15
2	15.102	0.2

Over these two trials, the silica gel was able to collect an average of 0.175 mL of water. At this rate, it is possible to project that approximately 0.47 mL would be collected over a complete 8-hour desorption cycle, although if also accompanied by a longer absorption cycle where more water was absorbed this number could be even larger. Another way of looking at this result is that at this rate, about 409 kg of silica gel would be required to meet the device's stated goal of producing 12.8 L per daily cycle. This scale is many times larger than the current device, although there are several other areas for improvement that could also improve the amounts of water that the device is able to produce. For example, ensuring the connections between the PVC pipe and funnels are completely airtight or adding additional pipes within the device to hold additional sorbents could aid in reducing losses to the ambient environment and increasing the amount of water the device can absorb. These ideas will be discussed slightly more in the Areas for Future Work section.

Besides the silica gel, one complete device trial was run using the Zeolite 3A. Due to the slow desorption rate of this material at the device's temperatures it was not expected that this trial would generate much water, but it was determined that it would still be worth trying once. After a three-hour desorption cycle, some small amounts of water had condensed in the tubing immediately outside of the device as shown in Figure 20 below, but none had yet reached the final collection beaker. Over a longer time period a couple of droplets may have eventually reached the beaker, although at the desorption temperature of 100 C it definitely would collect less water per time when compared to the silica gel. The zeolite may also be able to produce more water if the interior was at higher temperatures. However, this would require either continuing to use a strong electrical heat source or altering the original solar thermal absorber design. Additionally, this would probably require different material choices for some components, as something such as the PVC pipe would not hold up very well in significantly higher temperatures. As the device is currently designed however, these results clearly show that the silica gel is able to produce more water.

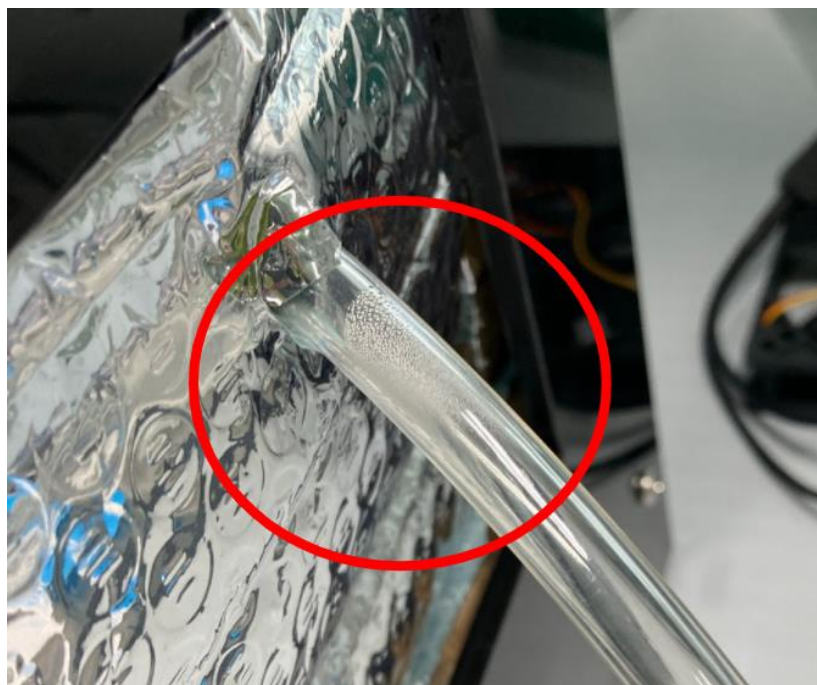


Figure 20 - Water condensed in exterior tubing during Zeolite 3A full device trial. No water reached the final collection site during this three-hour desorption cycle, although some of this condensed water may have over a longer time period.

6.3.4. Water Quality

Another very important measurement to ensure the water being collected is safe to drink is an analysis of the water quality. Specifically, quality measurements of interest include the pH and conductivity of the water since these are some of the most likely types of contamination to potentially come from the selected sorbent materials. Quality is not expected to be a significant issue since most of the water collected will have been through the vapor phase between its absorption to the sorbent materials and the final collection site, but these measurements will serve to confirm this intuition. It was originally planned to use meters available in the Active Learning Labs to measure these quantities, but these required a minimum of 10 mL of water to function properly. Since the volumes of water produced by the device did not meet this threshold, water quality strips were used instead. While these are not able to measure with the same precision as a more sophisticated meter, they still were able to give a general idea about the quality of the water being generated.

In total, water quality measurements were taken from three samples of collected water. From each of these, the first metric to be measured was pH. An example image of the result from one trial is included in Figure 21 below, and the results were the same from the other trials as well. In each case, the primary color of the testing strip showed a pH of 6. This result is not quite within the goal EPA standard range for pH of 6.5-8.5, although there are a few reasons that could explain this. First, since these strips cannot measure more precisely than whole integer values, the actual pH may have been slightly higher. Additionally, it is known that water vapor in the atmosphere is generally more acidic due to CO_2 dissolving in it and forming carbonic acid [56]. Therefore, since this device both captures water from the air initially and has

water travel through the vapor phase during the desorption cycle, it makes sense that the collected water might be slightly more acidic than standard drinking water that has been pre-treated. Fortunately, even this slightly lower pH should not present any safety issues. Other common beverages such as coffee can have even lower pH values, and the larger concern with more acidic drinking water is normally that it will leach metals from pipes involved in distribution [57]. However, since this device has no such materials that could lead to higher levels metals as water travels during the desorption cycle, there should be no such issue. Therefore, these results show that the water pH should not present any problems.



Figure 21 - Image of pH testing strip results from Trial 1. In each trial the results were closest to a pH of 6, which is relatively close to the EPA standard range of 6.5-8.5 when considering the lack of precision.

The other primary water quality metric of interest had been conductivity, although unfortunately it was not possible to directly measure this with the testing strips that were available in the Active Learning Labs. However, it was determined that measuring levels of sodium chloride might be a reasonable substitute. It is known that salts such as sodium chloride dissolve into ions in water, which can then conduct electricity. Therefore, a high concentration of sodium chloride would likely signify higher conductivity in a sample of water. As was done for pH, measurements of sodium chloride were taken from three samples of water generated by the device. The result for one of these trials is shown in Figure 22 below and is the same as the results from the other two trials. In each case, the measured sodium chloride level was at the lowest possible value for the strips used, 1500 ppm or less. For this reason, this also should not present a significant issue in terms of water quality. By proxy, it is also possible to conclude that conductivity should not be an issue either.



Figure 22 - Image of sodium chloride testing strip results from trial 1. In each trial the results showed a level of 1500 ppm or less, the lowest possible with the strips used. This low value means that sodium chloride, and by proxy conductivity, should not present any water quality issues.

Overall, these measurements show that, as expected, water quality should not be a significant problem for this device. It would certainly be a good check to measure quality with more sophisticated and precise tools if this device were improved to produce greater water volumes in the future, but overall, it should not be a major concern with this type of design.

6.4. Comparison to Technical Specifications

In Table 8 below, the various measurements described throughout this Measure & Verify section are compared to the initial project objectives as stated in the Technical Specifications. The third column marks whether the goal was met within the scope and timeline of this project, and a brief commentary on these final results is included afterwards.

Table 8 - Comparison of Results to Technical Specifications

Specification	Measured Value	Specification Met (Y/N)
Water pH: 6.5-8.5	Testing strips show ~6	~Y
Water Conductivity: < 1000 μ S/cm	Testing strips show sodium chloride level of 1500 ppm or less	~Y
Water Metal Levels: Aluminum: 0.02-0.2 mg/L	Unable to measure with water quality testing strips.	?
Operating Humidity: < 40%	RH in the lab setting averages between 20% - 30%	Y
Operating Absorption Cycle Temperatures: 10-30 C	Ambient temperatures during absorption cycles ranged from 19-22 C	Y
Device Energy Consumption from Electrical Grid: None	Sensors and fan are powered by external sources due to time restrictions.	N

Device Battery Specifications Required: 0.96 W/12 V	Battery not used due to time restrictions.	N
Incoming Airflow: 40 CFM	40 CFM (based on fan specifications [25])	Y
Sorbent Material Temperature During Desorption Cycle: 90-100C	Device reached goal temperature range in 20-30 minutes with hot plate as heat source.	Y
Water Production: 12.8 L/day	At current scale, the device is projected to produce 0.47 mL/day.	N
Device Size: Maximum 0.25 m ³	0.03125 m ³	Y
Sorbent Material Lifetime: 2 months	Device has not yet been tested over several months.	?
Device Cost: \$500	\$332.12	Y

The first few specifications in this table involve various water quality standards, for each of which the goal was to meet the EPA standard. As described in the Water Quality section the results obtained lacked some precision due to the use of water testing strips, but in general there should not be any water quality issues. Water generated by this device should be completely safe to drink, and therefore it can be considered that the spirit of these specifications has been met. Aluminum levels were not measured specifically as there was not a specific available testing strip, but for similar reasons they are not expected to be an issue in water generated by this device.

The following two specifications involve the conditions of the air that the device absorbs water from. Both the relative humidity and temperature of the ambient environment during all absorption cycle trials were within these goal ranges, proving that any water generated by the device did come from arid air. In other words, these operating conditions appropriately represented the arid regions of the globe that the device was targeted for, and these goals can be considered completely met.

After that, the next several specifications involve various electrical components of the device. While a fan rated for the desired airflow was implemented and the device interior did reach the necessary temperatures during the desorption cycle, both of these functions were ultimately powered by an external electrical source. Therefore, this device has not yet successfully met the goal of operating independently from an electrical grid. The solar panel and battery component was ultimately not designed due to a lack of time, but in the future should not be a very difficult addition in order to power the fan separately. For the heat source the solar thermal absorber certainly still requires additional testing with actual solar-level radiation, but a design similar to the one in this device still may be able to reach significantly higher temperatures. Overall, although several of these power-related goals were not met over the course of this project, it would almost definitely be possible to achieve them with additional development of this device.

Of the final few specifications listed in the table, the daily water production goal was certainly not met. While this project did prove conceptually that this method can generate water from the atmosphere, the device as currently constructed would need to be scaled up many times in order to produce 12.8 liters per day. In addition, while the goals for device size and cost were relatively easily met at the current scale, they would both likely increase if other changes to increase water generation were made. Finally, although research has suggested that these sorbent materials have lifetimes of several months before their absorption capacities reduce significantly, the timeline of this project did not allow this device to be tested for that long. This is certainly an area for potential future work.

Overall, many of the initial technical specifications for this device were met. For those that weren't, there are still clear future directions of development and testing that should allow the goals to be met eventually. For this reason, even though this device may not yet be able to produce enough water for somebody to live off of, this project can certainly serve as a proof of concept that in the future could turn into a very important source of drinking water.

7. Budget

Table 9 below shows all purchases made using the budget of ES100. Several other materials available in the Active Learning Labs were also used in this project, such as additional acrylic plastic sheets, screws and brackets, sensors and wiring for circuitry, and tape. Several devices and tools in the lab were also utilized for this project, including an oven, mass scale, and glass beakers. In general, efforts were made to keep costs low in order to keep this device accessible for greater numbers of people in various situations around the world. If a device such as the one built for this project were mass produced the cost could likely be slightly reduced, probably costing closer to \$250 or \$300. In the real world, the cost of the sorbent materials would be recurring, as users would need to purchase them a couple times each year in order to maintain an appropriate absorption capacity. However, a single user would only need to purchase one sorbent material rather than two. Finally, these costs would also likely be significantly higher if the device were scaled as is necessary to produce greater volumes of water. A detailed Bill of Materials is also included in Appendix 3.

Table 9 - Complete Budget

Item	Price (\$)	Source
Zeolite 3A (500g)	80	Sigma Aldrich
Silica Gel (100g)	80	Sigma Aldrich
Space Heater	23.64	Amazon
Plastic	59.90	Amazon
Adhesive	3.47	Amazon
Fan	6.99	Amazon
Aluminum	19.88	Amazon
Black Paint	5.48	Amazon
Insulation	9.88	Amazon
PVC Pipe	18.95	Amazon
Small Funnel	11.94	Amazon
3-pin to USB Adapter Cable	11.99	Amazon
Total	332.12	

8. Conclusions

Although this device does not yet produce enough water or somebody to live with, this project can certainly serve as a useful proof of concept. The device as built has shown that the strategy of using sorbent materials in separate absorption and desorption cycles can generate clean, liquid drinking water out of the atmosphere. Additional development of certain components, several of which are discussed in the Areas for Future Work section below, could help prevent losses and increase the total amount of water that the device captures, and at a larger scale this design would definitely be able to meet the daily goals set at the beginning of the project.

Another potential improvement that could come in the future for this device would be a greater availability of MOF sorbent materials. As described earlier in this report, these materials absorb similarly to Zeolite 3A at low RH and desorb at temperatures similar to the silica gel, but unfortunately are currently very expensive, difficult to source, and complicated to synthesize. The results of various experiments throughout this project have shown that the zeolite did absorb several times more water than the silica in arid conditions, and that the desorption temperature of the silica is about 75 degrees Celsius less than that of the zeolite. Taken together, these show that a MOF would surely be an optimal material for this application in terms of technical performance. As these materials likely become much more affordable and accessible with more research in the future, they could become another very promising pathway to improve this technology.

Overall, the work of this project shows that this device has a great potential to improve the lives of millions of people around the world. Especially for those potential end users living in arid, less developed regions, this strategy of pulling water from the air without any external electrical infrastructure would likely be one of the most viable solutions to provide clean drinking water. This would help to improve health outcomes for all people impacted, hopefully allowing more time for activities such as education and work. In the end, this device clearly has the potential to improve the quality of life for millions across the globe.

8.1. Areas for Future Work

Based on everything completed over the course of this project, there are still several interesting areas in which the work can be improved or expanded upon in the future. First, there are a few project components included in the original scope that still require additional testing or development. It will be important to test the solar thermal absorber design with a light source that accurately represents solar radiation. Whether this comes from a better lamp or actual solar radiation outdoors on a nice day, this testing will determine the maximum interior temperatures that the current design can obtain. This could then motivate potential iterations of the design if necessary. For example, adding a clear glass layer above the aluminum sheet could improve insulation of radiation outside of the visible spectrum, or changing the structure of the bottom of the aluminum sheet could influence how much heat it is able to transfer inside of the box. Showing that this method of converting solar radiation to thermal energy can reach the necessary temperatures during the desorption cycle will be a crucial step to ensuring that the device can function properly in rural areas as intended. The other element of the initial design that was not implemented over the course of this project due to time limitations was a solar

panel and battery unit. Once developed, this would serve to store solar energy gathered during the day and then power the small fan during the desorption cycle at night. Overall, it is not expected that this will be a very difficult system to design. It would primarily involve sizing the battery and solar panels based on the energy requirements of the fan being used.

Another component of the device that could certainly still be improved is the interior water collection mechanism. While the concept built for this project was successful in capturing some water, there are definitely ways that it could be improved to prevent losses to the surrounding air and to improve durability. First, improving the PVC to funnel connection point during the desorption cycle will be important. This is somewhat difficult because the ends of the pipe should be open during the absorption cycle to allow air through but closed during the desorption cycle to collect water. For this project, these connections were made with duct tape and Velcro tape to make this switch easy, but this choice also led to the connections being less airtight. This was a clear source of loss during the desorption cycle trials, as some water in the vapor phase would have definitely escaped through the available gaps. In the future, constructing this connection out of more robust materials to hold the two sides tightly together would help increase the volumes of water that can be collected. Additionally, during this project's trials the configuration changes made between the two cycles were done manually. In order to make operation easier for end users, automating this process could be very useful. At the same time however, this might require additional electronics and power which could present challenges. It at least would be an interesting addition to consider carefully.

Another interior configuration change that would help collect more water without scaling the box size would be to have multiple pipes holding sorbent materials running in parallel. While there certainly would be an upper limit on the amount that would fit without increasing the device size overall, even adding just a few additional pipes could greatly increase the amount of sorbent material that could reasonably be in the box at one time. This would in turn increase the amount of water that could be absorbed from incoming air and ultimately collected as a liquid. In order to do this, changes would likely have to be made in the ways the pipes are held and the funnels and tubing are connected in order to make everything fit. The final beneficial interior change would likely be to change some of the materials being used. For example, it was described how materials like the PVC pipe and duct tape began to deform after longer time periods at the highest temperatures of the operating cycle. Additional research and testing to determine different materials that can easily withstand temperatures around 100 C for many hours would serve to make the device more durable and prevent any potential accidents with parts wearing out quickly or breaking.

Finally, there are a few other additions or changes to the device that would likely increase its overall performance and reliability. The first of these has been mentioned multiple times throughout this report and involves the use of MOFs as the primary sorbent material. Although this might not be possible in the immediate future due to cost and availability, it would be very useful to test them within the device if that ever became a feasible option. More immediately, it would also be a good idea to test this device over a longer period of daily water collection. It is expected that any sorbent material will lose some of its capacity to hold water after many cycles of absorption and desorption and testing the device over several months would provide good data on how quickly this absorption capacity decreases. This could then inform decisions on how often it is recommended for users to replace the sorbent material. The final potential area for future work involves filtration of air before it enters the device. While the

air in the lab setting for trials during this project was relatively clean, air that the device might be pulling water from in dry, arid environments could have significant levels of suspended particles. These could in turn impact the quality of the water collected or coat the sorbents and reduce their abilities to absorb water. Therefore, adding some kind of simple air filter before the fan during the absorption cycle would likely be beneficial in preventing any of these potential problems. Together, all of the developments described in this section should help the device reach a stage where it is ready to be deployed in arid regions of the world to generate drinking water.

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10. Appendices

10.1. Appendix 1: Relevant Engineering Standards

Some of the most important standards that have been considered so far in this project are the EPA drinking water quality standards. It is crucial that any water generated by this device is safe to drink, and these commonly used values have been set as benchmarks that must be achieved to ensure that the water quality is sufficient. All water collected in any experimental trials will be measured using specific instruments in the lab and compared to these standards to ensure that it is safe. If not met, then the device would not be an appropriate drinking water source and elements of the design may need to be iterated upon further.

10.2. Appendix 2: Non-Technical Contexts

Besides the many technical details and considerations that have been discussed throughout this report, there are also a variety of non-technical contexts that have influenced my project. First of all, one of the primary goals of this project is to improve public health around the world by providing a clean drinking water source in areas that may not yet have access to any other. This would help to prevent numerous dangerous waterborne illnesses that infect and unfortunately kill many people each year. By providing a new source free of contamination, it would keep more people healthy and extend lifetimes around the world. This project has also considered environmental factors since the device must be able to operate in specific arid conditions where the relative humidity is less than 40%. These environmental conditions are reproduced for any testing of the device and are a critical metric of success. Global factors are also considered since this device would likely be used primarily in less developed regions of the world. These are the areas where clean water sources most often do not already exist, and therefore the contexts of these communities must be considered. For example. This is the primary reason why I have chosen to design the device to operate without any external power source. In many of these communities, there may not be an electrical grid or other source of power, and therefore the device must be able to function independently.

Cultural and social factors were also very important in the motivation and design choices behind this device. In many communities without easy access to clean drinking water, it is often women or children who are required to make long journeys to collect water. This is one of the reasons why I chose to design the device at a size that would serve one family. In this way, each home in a community could have one device, and even if these traditional cultural and social roles remained, these people could collect water much more quickly and therefore have more time for activities like education. In order for this to be feasible, the economics of the device also were carefully considered to make it as affordable as possible. For this reason, all materials were considered carefully to keep overall device costs as low as possible. This is especially true with the sorbent materials, some of which had very high prices. Overall, all of these non-technical contexts were just as important as technical details in the design of this device.

10.3. Appendix 3: Bill of Materials

BOM (Bill of Materials)	Unit Cost \$	Unit	# of Units	Total \$	Exact or estimated?
Zeolite 3A Sorbent Material	\$ 80.00	500 g container	1	\$ 80.00	Exact
Silica Gel Sorbent Material	\$ 80.00	100 g container	1	\$ 80.00	Exact
Space Heater	\$ 23.64	1	1	\$ 23.64	Exact
Acetal Plastic Sheets	\$ 29.95	3 pack of 12"x24"x0.12	2	\$ 59.90	Exact
Plastic Adhesive Glue	\$ 3.47	4 mL tube	1	\$ 3.47	Exact
Computer Case Fan	\$ 6.99	1	1	\$ 6.99	Exact
Aluminum Sheet	\$ 19.88	24"x12"x0.019"	1	\$ 19.88	Exact
Flat Black Protective Enamel Paint	\$ 5.48	8 oz. jar	1	\$ 5.48	Exact
Aluminum Bubble Thermal Insulation	\$ 9.88	16"x5' roll	1	\$ 9.88	Exact
2" Sch40 PVC Pipe	\$ 18.95	2ft. Length	1	\$ 18.95	Exact
Small Plastic Funnels	\$ 5.97	1	2	\$ 11.94	Exact
3-pin to USB Adapter Cable	\$ 11.99	1	1	\$ 11.99	Exact
Please do your best to fill in the	Total \$		Exact or estimated?		If you had to use CNS space and equipment please
Total Development cost: everything that	\$ 332.12		Exact		Why did your project require the use of CNS facilities?
What is the minimum cost to make one	\$ 300.00		Estimated		Roughly much time did you spend using CNS facilities? (specify hours or days)
Total cost of items purchased through the	\$ 332.12		Exact		What equipment did you need to use?
Total cost covered by the Harvard	\$ -		Exact		Who did you interact with at CNS and how?
Total cost of items purchase personally, if	\$ -		Exact		If you are affiliated with a research lab that
Total cost covered by a non-Harvard lab	\$ -		Exact		If you didn't work through a research lab directly, did
					What could we have done better to make your CNS
Please list below all material used in					
Additional Acrylic Plastic					
Light borrowed from Glen					
Screws and Brackets					
RH/Temperature Sensors, Wiring, Resistors, Microcontroller, Breadboards					
Duct Tape					
Mass Scale					
Glass Beakers (returned)					
Small Plastic Trays					
Laboratory Oven					
Velcro Tape					
Hot Plate					
Plastic Tubing					

10.4. Appendix 4: Arduino Code for DHT22 Sensors

The following code was adapted from the Adafruit website for DHT22 series RH and temperature sensors [44]. This code reads out relative humidity and temperature from sensors in two locations every two seconds, allowing the external and internal conditions of the device to be monitored throughout all trials.

Code:

```
// Example testing sketch for various DHT humidity/temperature sensors
// Written by ladyada, public domain

// REQUIRES the following Arduino libraries:
// - DHT Sensor Library: https://github.com/adafruit/DHT-sensor-library
// - Adafruit Unified Sensor Lib: https://github.com/adafruit/Adafruit\_Sensor

#include <DHT.h>
#include <SPI.h>
#include <SD.h>
#include <Wire.h>

#define DHTPIN 2 // Digital pin connected to the DHT sensor
#define DHTPIN 1

// Feather HUZZAH ESP8266 note: use pins 3, 4, 5, 12, 13 or 14 --
// Pin 15 can work but DHT must be disconnected during program upload.

// Uncomment whatever type you're using!
// #define DHTTYPE DHT11 // DHT 11
#define DHTTYPE DHT22 // DHT 22 (AM2302), AM2321
// #define DHTTYPE DHT21 // DHT 21 (AM2301)

// Connect pin 1 (on the left) of the sensor to +5V
```

```
// NOTE: If using a board with 3.3V logic like an Arduino Due connect pin 1
// to 3.3V instead of 5V!
// Connect pin 2 of the sensor to whatever your DHTPIN is
// Connect pin 3 (on the right) of the sensor to GROUND (if your sensor has 3 pins)
// Connect pin 4 (on the right) of the sensor to GROUND and leave the pin 3 EMPTY (if your
// sensor has 4 pins)
// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor
```

```
// Initialize DHT sensor.
// Note that older versions of this library took an optional third parameter to
// tweak the timings for faster processors. This parameter is no longer needed
// as the current DHT reading algorithm adjusts itself to work on faster procs.
DHT interior = DHT(2, DHT22);
DHT exterior = DHT(1, DHT22);
```

```
void setup() {
  Serial.begin(9600);
  interior.begin();
  exterior.begin();
}
```

```
void loop() {
  // Wait a few seconds between measurements.
  delay(2000);

  // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
  float inth = interior.readHumidity();
  float exth = exterior.readHumidity();
  // Read temperature as Celsius (the default)
  float intt = interior.readTemperature();
```

```

float extt = exterior.readTemperature();
// Read temperature as Fahrenheit (isFahrenheit = true)
float intf = interior.readTemperature(true);
float extf = exterior.readTemperature(true);

// Check if any reads failed and exit early (to try again).
if (isnan(inth) || isnan(exth) || isnan(intt) || isnan(extt) || isnan(intf) || isnan(extf)) {
    Serial.println(F("Failed to read from DHT sensor!"));
    return;
}

// Compute heat index in Fahrenheit (the default)
float inthif = interior.computeHeatIndex(intf, inth);
float exthif = exterior.computeHeatIndex(extf, exth);
// Compute heat index in Celsius (isFahreheit = false)
float inthic = interior.computeHeatIndex(intt, inth, false);
float exthic = exterior.computeHeatIndex(extt, exth, false);

Serial.println(F(""));
Serial.print(F("Interior RH & T: "));
Serial.print(inth);
Serial.print(F("% "));
Serial.print(intt);
Serial.print(F("°C "));
Serial.print(F("Exterior RH & T: "));
Serial.print(exth);
Serial.print(F("% "));
Serial.print(extt);
Serial.print(F("°C "));

}

```