Design of a Modular Cloud Chamber with an Internal Clock Mechanism

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On my honor as a University Student, I have neither given nor received aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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1. Introduction

Every second, innumerous quantities of cosmic radiation bombard the Earth's atmosphere. According to the Center for Disease Control, cosmic radiation includes high-energy charged particles as well as x-rays and gamma rays (CDC, 2015). These particles are all around us and invisible to the naked eye.

The initial prompt for this capstone project was to design and develop a machine that does not exist and fulfills a useful purpose. In response to this prompt, our group worked to design and develop a cloud chamber clock, a way to view these particles all around us. This project idea combined the function of a cloud chamber while also telling the time, a machine that did not exist prior to this capstone. Additionally, this project would serve its purpose as a piece of kinetic art, a machine that has moving parts combining with an aesthetic display.

For some context, a cloud chamber is a tool used for visualizing ionizing radiation and was first invented in the early 1900s by Charles Wilson. Cloud chambers are a type of passive particle detector, as they do not directly create or energize particles unlike large-scale modern ones such as the Large Hadron Collider. They are able to illuminate the paths of radioactive particles by forcing alcohol vapor into a supersaturated state where the alcohol droplets condense around ionized (usually radioactive) particles as they fly by. Figure 1 below shows the trails of particles as visualized by a cloud chamber.

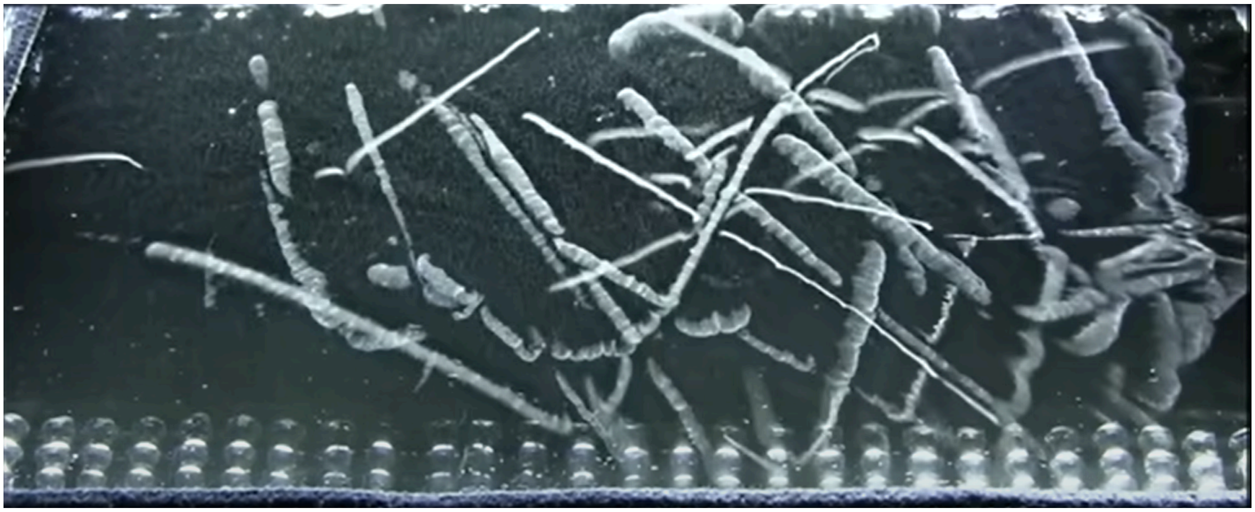


Fig. 1: Example image of radioactive particles visible in a cloud chamber (Cloudylabs).

The alcohol vapor in the chamber is at such a high saturation (supersaturated past the normal limits of what the air can hold) that it condenses into liquid form when catalyzed by the presence of a subatomic particle. Thus, what the chamber is actually illuminating is a string of alcohol droplets that follow the path of a radioactive particle, not the actual particle itself. Yet, this mechanism has been significantly helpful in the promotion of science in the field of quantum discovery since its inception in the early 1900s.

Unlike cloud chambers, clocks are an extremely widespread ancient invention well-studied by many civilizations. Clocks are used for timekeeping and have been created in many different forms, including sundials, mechanical watches, water clocks, analog wall clocks, digital clocks, atomic clocks, and more. Despite the ubiquity of clocks in modern society, the mechanism for designing a well-functioning clock is quite challenging. This task is especially difficult when combining the clock mechanism within the confines of a sealed chamber, as was the case in this project.

2. Objectives

The main objective of this project was to create a reusable and modular clock inside of a cloud chamber to serve as an educational science demonstration. Secondary objectives included providing an experiential learning opportunity for a senior mechanical engineering capstone project through both design and manufacturing phases as well as designing an aesthetic piece of kinetic art.

3. Cloud Chamber Design

3.1 Chamber System Overview

The cloud chamber was subject to several main constraints, including: containing reusable components, being aesthetically appealing, being able to accurately tell the time, and being as simple as possible. The last constraint was the most impactful due to the limited time and budget available in the one-semester capstone course. The constraint of reusability limited several design choices so that the project would be able to be used in the future as a science demonstration and allow for necessary changes, upgrades, or maintenance. This is related to the aesthetics of the design, since a public demonstration needs to be visually appealing in order to capture interest. The last constraint of telling time is necessary to fulfill one of the main objectives and allow the cloud chamber clock to function as its name implies.

Different views of the full cloud chamber clock assembly as designed are shown in Figure 2 below.

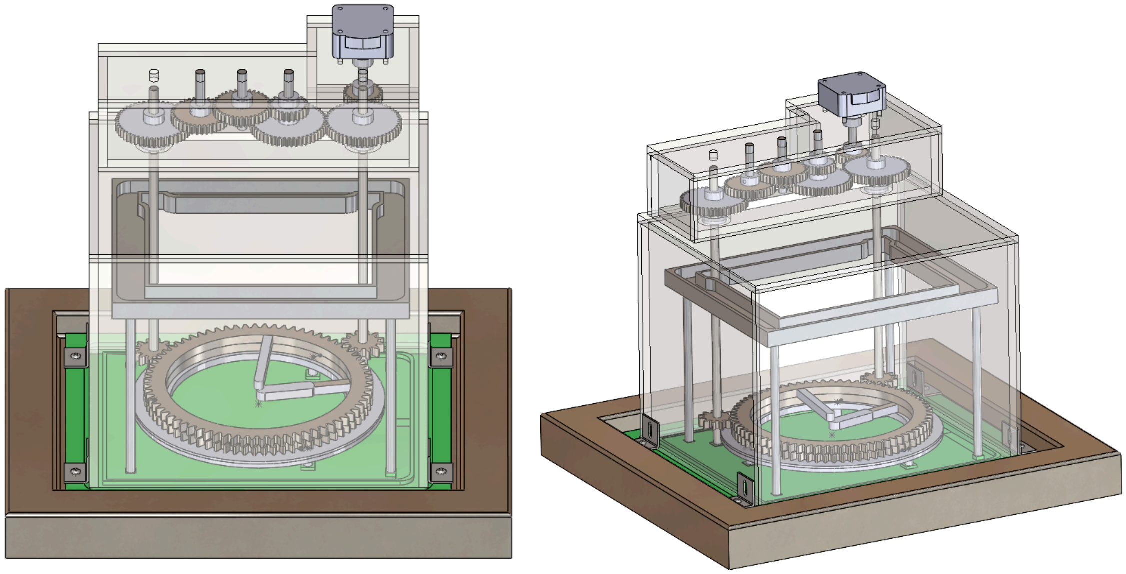


Fig. 2: Front and angled views of the entire cloud chamber clock assembly (created by authors).

The chamber's external dimensions are approximately 8.875 x 10.375 x 7.5 in. There is also a gearbox mounted on the back of the chamber top with an additional ~2.98" in height. Due to its fairly compact nature, the entire cloud chamber clock assembly is easy to transport and view. The major components include the clock ring gears and clock hands, isopropyl alcohol reservoir, gearbox, cold plate, chamber walls, and motor. The entire assembly is mounted on the compressor table of a rolled ice cream machine. More detail about these systems are given in the following sections. Figure 3 below depicts these components.

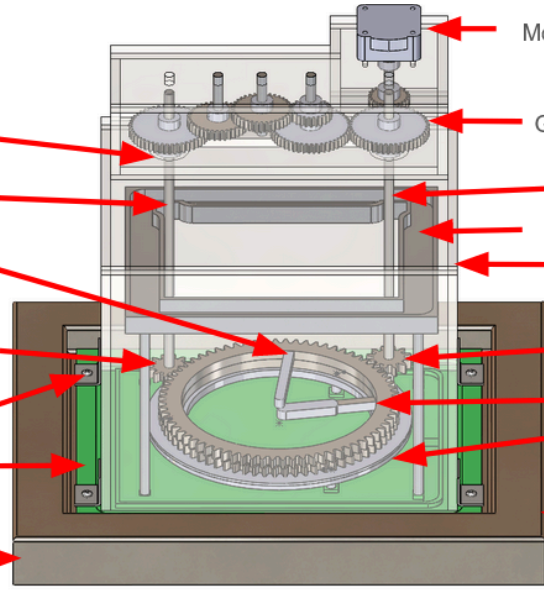


Fig. 3: Labeled assembly view of the entire cloud chamber assembly (created by authors).

The cloud chamber clock is very modular - few pieces are permanently attached to each other, so components can be removed separately for maintenance, repair, or replacement. For example, the motor, gears, gearbox, shafts, reservoir, chamber itself, ring gears, and cold plate can all be removed separately. The cloud chamber clock is also very simple, as seen in the previous images. Simple geometries and assembly methods were used to hasten the prototyping and manufacturing process and improve reliability. Simplicity was favored over robustness in order to meet the desired goals of modularity, reusability, and ease of design and manufacturing during the limited time available. An example of this is seen in how the entire clock uses only a single power source, the motor, much like a typical analog clock. The motor would drive a gear that would drive a shaft to control the rotation of the minute hand. The rotating minute hand shaft would transmit its power through a gearbox that reduces the speed of the rotation to 1/12 that of the original minute hand shaft. The final output of the gearbox would then drive the hour hand shaft.

The cloud chamber clock was intended to be operated as follows. Pure isopropyl alcohol would be filled in the reservoir. Then, the rest of the chamber systems would be set in position and the clock hands would be set manually by turning the minute hand shaft. The cold plate would be cooled to approximately -30 °C using the ice cream machine compressor table and heating elements would be turned on so the chamber top would reach approximately 40 °C. Alcohol would evaporate, encouraged by the heating elements, and would saturate the air. Through natural convection and diffusion alone, alcohol vapor would become supersaturated near the bottom of the cloud chamber and begin to condense around passing charged particles (typically ionizing radiation). While this is happening naturally, the clock would be operating nominally through power provided by the motor. The clock hands would be made of TIG welding electrodes; these are made of tungsten and would be 2% thoriated to contain radioactive thorium-232, which emits charged alpha particles. The clock hands would thus be emitting visible radiation, seen through condensed particle trails, that would supplement the naturally occurring background radiation that would be visible in the cloud chamber. The final clock in operation would be simple, aesthetically appealing, and able to operate continuously with little human action required.

3.2 Material Selection

Isopropyl alcohol was chosen for the vapor material due to its high vapor pressure and ease of procurement. Its vapor pressure is much higher than that of water, allowing for more rapid evaporation and ease of supersaturation inside the cloud chamber. For example, at 23.8 °C (approximately room temperature), its vapor pressure is 40 mmHg (Wikipedia, n.d.). Figure 4 below shows a table of vapor pressure for isopropyl alcohol across a range of temperatures.

P in mm Hg	1	10	40	100	400	760	1520	3800	7600	15200	30400	45600
T in °C	−26.1	2.4	23.8	39.5	67.8	82.5	101.3	130.2	155.7	186.0	220.2	—

Fig. 4: Isopropyl alcohol vapor pressures, in mmHg, across a range of temperatures. (Wikipedia, n.d.).

At -26.1 °C, the vapor pressure is just 1 mmHg, indicating that the isopropyl alcohol will exist primarily in the liquid phase at this temperature. Thus, a temperature in this approximate range for the cold plate was chosen to facilitate condensation out of the supersaturated phase and the production of particle trails. More detail is given in Sections 3.3-3.4 about related design and equipment selection. High-purity (99%) isopropyl alcohol was used to limit the effect of contaminants and water lowering its rate of evaporation.

Materials for the chamber itself were selected based on thermodynamic properties, chemical compatibility with isopropyl alcohol, and cost. Aluminum was chosen as the bottommost cold plate of the chamber due to its low cost, high machinability, relatively high thermal conductivity, and compatibility with isopropyl alcohol due to the formation of an oxide layer on exterior surfaces exposed to air. It was also used for reservoir support legs and shafts for the previous reasons and its strength and dimensional stability as a metal. Aluminum is generally noted as having “good” chemical compatibility with isopropyl alcohol, as it is insoluble in it and is fairly resistant to corrosion due to the oxide layer (CP Lab Safety, n.d.a).

Acrylic was chosen for the chamber wall and gear materials primarily due to its ease of manufacturability. Access to a laser cutter was provided, allowing 2D designs to be easily and quickly be cut from acrylic sheets using the AutoCAD DXF file format. Acrylic can also be glued to other acrylic pieces using purpose-made acrylic solvents that dissolve parts of the pieces and allow them to be joined together again in a process much like the welding of metals. This choice of material allowed for rapid prototyping of simple assemblies at a low cost and faster pace than through the use of 3D printing. In addition, acrylic is fairly resistant to isopropyl alcohol - while some sources have found “some effect” of constant exposure to isopropyl alcohol (including swelling or softening), the temperatures and quantities of isopropyl alcohol used in this project were lower than used in tests (Zazo, A., 2014). The instructor also submerged pieces of acrylic in isopropyl alcohol for at least a day and observed no significant structural or chemical damage, shown in Figure 5 below. The acrylic pieces all bore little load, so minute damage or surface defects were not considered significant issues.

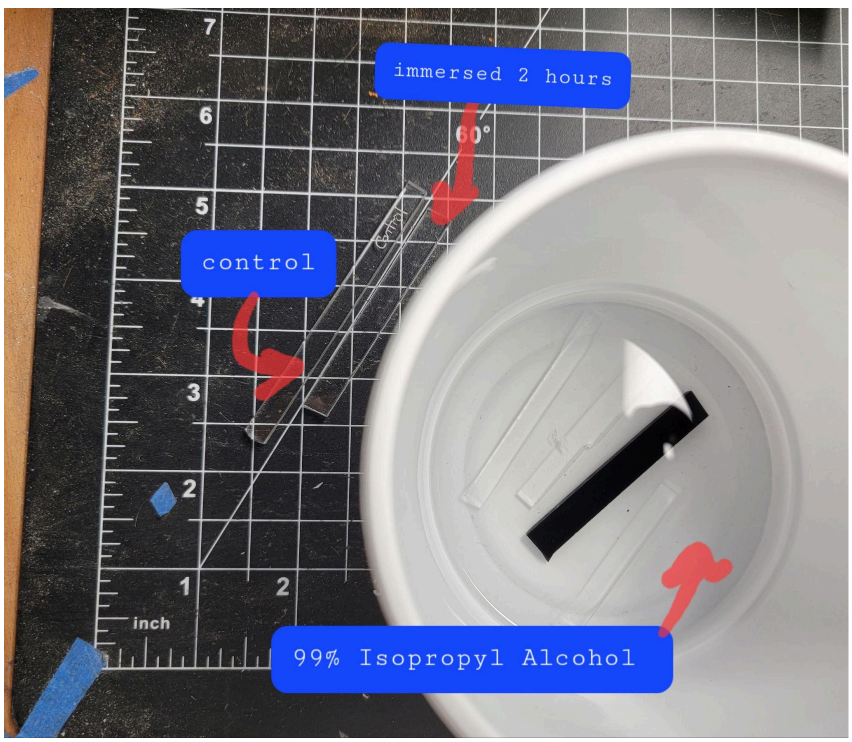


Fig. 5: Isopropyl alcohol damage test on acrylic, performed by the instructor. No significant damage was observed (created by the authors).

Polypropylene was chosen for the reservoir material due to its very high chemical resistance to a variety of organic solvents, including isopropyl alcohol (CP Lab Safety, n.d.b).

Polypropylene is inexpensive, commonly available in sheets, and is easily machinable. Unlike acrylic, it cannot be laser cut, so its use was limited to the reservoir.

3.3 Thermodynamic Analysis

As previously mentioned, the operation of a Langsdorf-type diffusion cloud chamber requires the production of supersaturated vapor. For simplicity, this chamber uses temperature gradients to encourage high evaporation of the fluid (isopropyl alcohol) into vapor near the top of the chamber. The vapor then naturally diffuses downwards in a decreasing temperature gradient driven by the temperatures of the cold plate and heating elements (if included). As shown in Section 3.2, saturation vapor pressure decreases with decreasing temperature, so assuming sufficient alcohol has evaporated to reach saturation in the higher-temperature region, the vapor will become supersaturated near the colder bottom of the chamber and begin to condense. Since the chamber will be kept sealed and with few foreign contaminants, this condensation will be greatly hastened by the passage of charged particles serving as condensation nuclei.

The Clausius-Clapeyron relation describes the relation between saturation vapor pressure of a single compound on temperature (LibreTexts, n.d.). The equation below relates the saturation vapor pressure at one temperature to a known vapor pressure at another temperature, given the enthalpy of vaporization.

$$\ln\left(\frac{P_2}{P_1}\right) = -\frac{\Delta H_{\mathrm{vap}}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Fig. 6: A derived form of the Clausius-Clapeyron relation, assuming an ideal gas for the vapor form of a liquid (LibreTexts, n.d.).

Using known properties of isopropyl alcohol, a saturation vapor pressure vs temperature curve was obtained, then transformed into Figure 7 below using assumed chamber properties (Wikipedia, n.d.). This methodology follows that used by Langsdorf in his original 1939 paper on the diffusion cloud chamber.

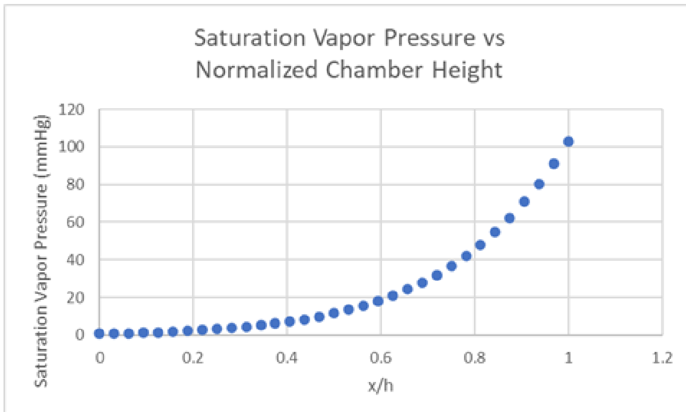


Fig. 7: Saturation Vapor Pressure vs Normalized Chamber Height (relative height above the bottom of the chamber). This curve uses the Clausius-Clapeyron relation and assumes a linear temperature gradient (created by authors).

Figure 7 above assumed a chamber height of 16 cm and a linearly distributed temperature range from the chamber bottom to top of -30 to 40 °C to give a temperature relation of $T(x) = 4.375x - 30$, where x is the height above the chamber bottom in centimeters. Given values were a known saturation vapor pressure of 100 mmHg at 39.5 °C, enthalpy of vaporization of 45.3 kJ/mol, universal gas constant of 8.314 J/K/mol, molar mass of 60.1 kg/kmol (Wikipedia, n.d.). The temperature relation and values were substituted into the Clausius-Clapeyron relation to yield a variation of saturation vapor pressure with chamber height: $P(x) = 100 * e^{-45300/8.314 * \frac{1}{4.375x + 243.15} - \frac{1}{312.65}}$, where x is again height above the chamber bottom. Chamber height was then normalized to form the curve shown in Figure 7 above. Right at the cold plate (a height of 0), saturation vapor pressure would be approximately 0.69 mmHg - there would be very little vapor at all here.

Using the results above, the formation of condensed particle tracks from ionizing radiation would most likely occur near the bottom of the chamber where saturation vapor pressure is lowest, causing the vapor to become supersaturated - condensation is most likely to occur here. Langsdorf found that supersaturation, the ratio of actual vapor pressure to saturation vapor pressure caused by diffusion, would peak approximately 10% of the chamber height above the bottom (Langsdorf, 1939). Figure 8 below illustrates this using the parameters of Langsdorf's specific cloud chamber.

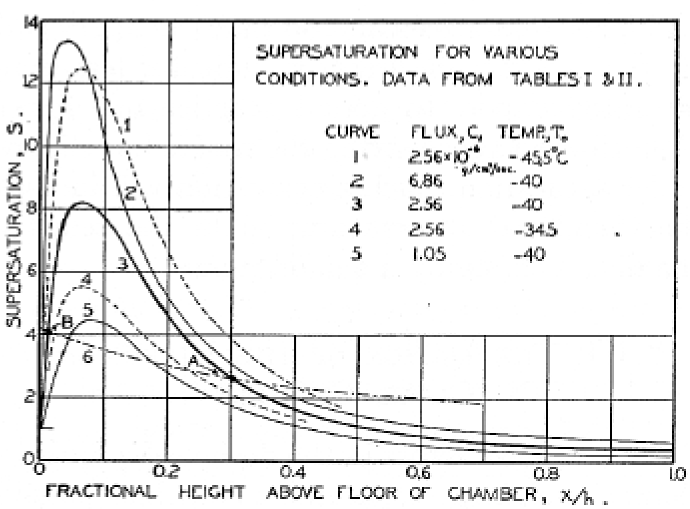


Fig. 8: Supersaturation vs fractional height above the bottom of Langsdorf's cloud chamber. The conditions differ from those used in this project's chamber but still demonstrates how supersaturation, and thus condensation around charged particles, is most likely to occur near the bottom of the chamber (Langsdorf, 1939).

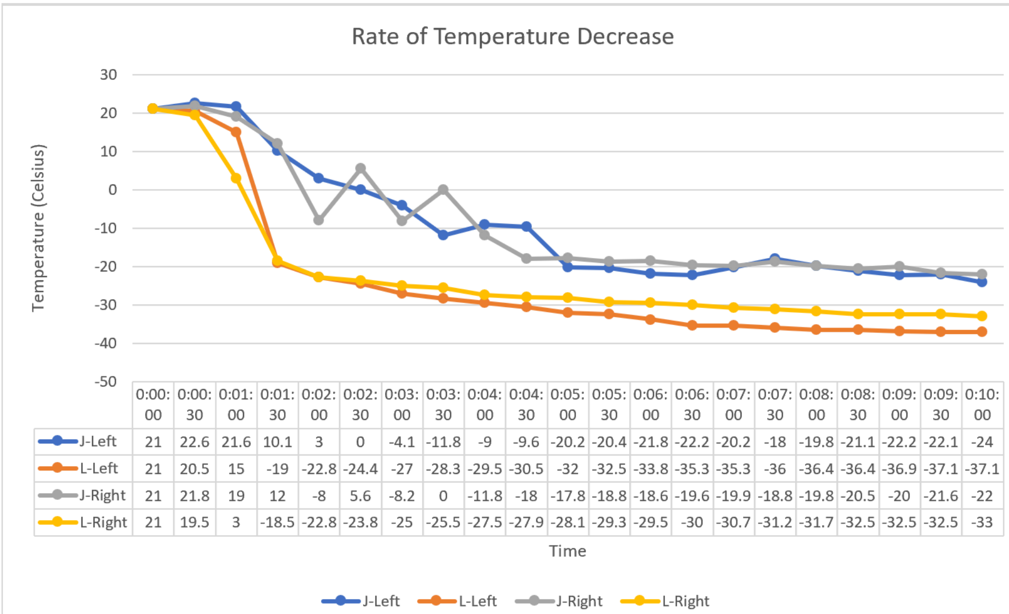
The results above imposed the general constraint of keeping the clock ring gears as close to the bottom of the chamber as possible to encourage the visibility of ionized particles near the clock. These results also assumed that the top of the chamber would be heated to encourage evaporation.

3.4 Compressor-Cooled Ice Cream Machine

To provide the cooling required by the cloud chamber, as well as support the objectives of reusability and modularity, a commercial rolled ice cream machine was chosen. This style of ice cream machines are characterized by a flat surface for preparing ice cream, which the cloud chamber could be placed upon. A VEVOR brand rolled ice cream machine (Amazon ASIN B092CL4F4L), shown below in Figure 9, was selected. This machine is compressor-cooled, allowing for continuous operation and temperatures of up to -30 °C.

Fig. 9: The VEVOR brand ice cream machine selected for the cold plate element of the cloud chamber (created by authors).

Initial complications arose when the first VEVOR brand ice cream machine failed to reach the desired temperature range in initial tests with infrared thermometers. Evaluating the reviews of the project, it was deemed this first machine had experienced a malfunction either in shipping to the university or in the initial manufacturing of the product. Since the likelihood of visible particle tracks occurring hinged on a working ice cream machine, two more of the same model of VEVOR ice cream machine were purchased to be tested. To evaluate which machine worked best for the required conditions, an experiment was conducted where both machines were evaluated at the same time. Over the course of the first ten minutes of cooling for both machines, the temperatures were measured and recorded to determine the fastest cooling rate of the two machines. The data was then analyzed and led to the selection of one of the machines for prototyping purposes.



	0:00:00	0:00:30	0:01:00	0:01:30	0:02:00	0:02:30	0:03:00	0:03:30	0:04:00	0:04:30	0:05:00	0:05:30	0:06:00	0:06:30	0:07:00	0:07:30	0:08:00	0:08:30	0:09:00	0:09:30	0:10:00
J-Left	21	22.6	21.6	10.1	3	0	-4.1	-11.8	-9	-9.6	-20.2	-20.4	-21.8	-22.2	-20.2	-18	-19.8	-21.1	-22.2	-22.1	-24
L-Left	21	20.5	15	-19	-22.8	-24.4	-27	-28.3	-29.5	-30.5	-32	-32.5	-33.8	-35.3	-35.3	-36	-36.4	-36.4	-36.9	-37.1	-37.1
J-Right	21	21.8	19	12	-8	5.6	-8.2	0	-11.8	-18	-17.8	-18.8	-18.6	-19.6	-19.9	-18.8	-19.8	-20.5	-20	-21.6	-22
L-Right	21	19.5	3	-18.5	-22.8	-23.8	-25	-25.5	-27.5	-27.9	-28.1	-29.3	-29.5	-30	-30.7	-31.2	-31.7	-32.5	-32.5	-32.5	-33

Fig. 10: Graph depicting the change in temperature for each machine. The machines were labeled Left and Right and measured by both Julian and Luca. Julian's thermometer led to unreliable temperature readings and were disregarded (created by authors).

The left ice cream machine with lower asymptotic and final temperatures was chosen. It reached a minimum of approximately -33 °C, which was more than sufficient to achieve the ideal temperature gradient and supersaturation levels required for particle tracks to visibly condense.

3.5 Cold Plate

The cold plate is the bottommost part of the cloud chamber and was designed to be machined from a 0.25" thick sheet of 6061 aluminum. The main purpose of the cold plate is to provide a way to assemble and mount all components of the cloud chamber. It also protects the surface of the compressor table of the ice cream machine from corrosion due to excessive exposure to isopropyl alcohol. Since the plate is an additional thermal mass between the coldest part of the assembly, the ice cream machine itself, it had to be thermally conductive to still allow the bottom of the main cloud chamber to be sufficiently cold. Otherwise, a warmer “cold plate” would have an unacceptably high saturation vapor pressure near the bottom of the cloud chamber and delay or prevent supersaturation, and therefore visible particle condensation trails, from occurring. Due to these constraints, a thin aluminum sheet was chosen for this material. As mentioned in Section 3.2, this alloy of aluminum was chosen for its high thermal conductivity, commercial availability, low cost, and chemical resistance to isopropyl alcohol. It was planned to be machined using the CNC available in the MILL (MEC B014). Figure 11 below shows a view of the entire cold plate.

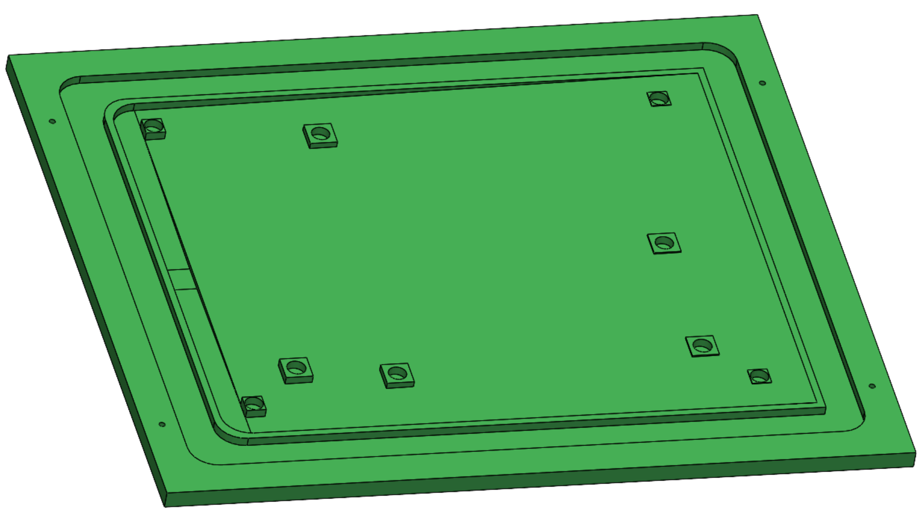


Fig. 11: Cold plate with all features visible (created by authors).

The cold plate had several key features to enable a simple assembly that could easily be removed. On the outermost border, there are four tapped 6-32 holes for mounting angled brackets to fix the chamber in place. There is a filleted groove running around the perimeter to hold the chamber walls. A silicone rubber sheet would be cut to line the groove to ensure the chamber walls were sealed and did not allow condensed isopropyl alcohol to leak out through the bottom. Inside the groove, a thin wall houses the main chamber and clock area. There are four square supports on the inside of the main chamber area, near the corners, to support the reservoir legs. Each support has a flat-bottomed cylindrical hole the legs rest inside, preventing undesired movement while still allowing the reservoir to be easily removed when needed.

There are two additional square supports near the bottommost reservoir leg supports that support the two shafts driving the hour and minute hand ring gears. These supports also have a flat-bottomed cylindrical hole for the shafts to rotate freely in while preventing undesired movement or wobbling. They are carefully positioned to precisely mate the driver gears with the ring gears so that their pitch circles are tangent. Bearings would allow for lower friction rotation of the shafts with no sliding, but would take up additional space on the bottom and are also likely to corrode. Constant exposure to isopropyl alcohol, which likely contains water and other impurities even at a high concentration, would degrade the steel used in most bearings. Thus for simplicity, a simple hole for the shafts to rotate in was chosen over other options. The shafts are rotating slowly enough to avoid significant wear and be affected significantly by the friction of the aluminum.

Three additional square supports located nearest the center of the cold plate are positioned equispaced at 120° apart to support the ring gear assembly. The ring gears rest on a non-rotating support ring (described in Section 4.2), which itself is supported by three cylindrical legs that rest inside these three supports on the cold plate. The supports also have flat-bottomed cylindrical holes to prevent unwanted movement and allow for simple removal of the ring gears.

Another purpose of the cold plate was to collect condensed isopropyl alcohol into a single area for collection and reuse (described in Section 3.8). To achieve this, the entire main chamber area of the cold plate was designed to be inclined 0.92° with respect to the horizontal leading to a collection zone. Figure 12 below shows a section view through the center of the cold plate showing the incline.

Fig. 12: Longitudinal section view of the cold plate showing the incline (created by authors).

The collection zone is located on the leftmost side in Figures 11 and 12 above. This shallow incline was primarily driven by the constraint of the cold plate being required to be thin - this left little vertical height to form an incline.

The collection zone itself was further inclined towards a central collection point, shown in Figure 13 below.

Fig. 13: Section view of the collection zone, oriented perpendicular to the previous section view (created by authors).

The collection zone was inclined 1.14° with respect to the horizontal, again constrained by material thickness and dimensional constraints of the remaining chamber area.

The majority of the cold plate was designed to be easily machined using an ⅜” diameter end mill. The fillets of the chamber groove were ⅜” in radius to support this. The collection zone was 0.39” in width to enable it to be machined more quickly using this larger bit. Only the cylindrical holes of the supports for the legs and shafts required a 0.25" end mill diameter due to the size of aluminum rods used.

3.6 Reservoir

The reservoir contains the isopropyl alcohol and is elevated so the alcohol can be located at a higher elevation, closer to a heat source at the top to encourage evaporation and diffusion of saturated vapor downwards. It was supported by four cylindrical aluminum legs 0.25" in diameter at its corners. An image of the reservoir is shown in Figure 14 below.

Fig. 14: Reservoir CAD view (created by authors).

The reservoir was constrained by visibility and the position of the ring gear driver shafts. It was elevated 5" above the bottom of the chamber so it could be heated and encourage evaporation of the alcohol, so it was designed to be as unobtrusive as possible to avoid obstructing the view of the clock and chamber any more than necessary. The reservoir was thin (0.5" total thickness) and the main trough was shaped like a hollow rectangle when viewed from the top (1" thickness viewed from the top). However, to hold a sufficient quantity of alcohol and allow for an extended operation time, the reservoir walls were made thin, with a ⅛” thickness on the sides and bottom. This allowed the reservoir to be able to comfortably hold approximately 100 mL of isopropyl alcohol, enough to operate the chamber for over 90 minutes continuously.

Since the two driver shafts were located along one of the long sides of the chamber, the reservoir had to account for their position to avoid interference. Therefore, two cutouts were included along one side of the reservoir, as shown in Figure 14. This allowed the reservoir to still hold a sufficient volume of alcohol, while remaining balanced with symmetric leg placement. The reservoir could also be removed separately from the clock assembly.

The reservoir was freestanding and supported no load except the weight of the alcohol, allowing the walls to be thin. Like the cold plate, it was designed to be machined by CNC machine using a ⅜” diameter end mill. As such, ⅜” radius fillets were added to all interior corners of the reservoir.

The legs were tapped on one end and attached to the bottom of the reservoir using 6-32 thread set screws. Each leg screwed into a tapped acrylic plate ⅛” thick that was glued onto a bottom corner of the reservoir. This allowed the entire reservoir to be lifted as one piece while allowing for disassembly and removal of the legs.

3.7 Heating Elements

A heating element would serve two purposes in the cloud chamber. The first is to prevent condensation on the viewing surface to maintain visibility. The second is to assist in evaporation of the alcohol and to maintain the temperature gradient already described. The wire was to be attached to the top surface of the cloud chamber similar to the heating elements on a vehicle’s rear windshield. Nichrome wire was selected for this purpose due to its large resistance values and high temperature ratings. Multiple sizes of Nichrome 80 (80% Ni, 19.5% Cr, 1.5% Si) were acquired for experimentation (MWS, n.d.). Due to delays on the cloud chamber portion of the project, no further designs or experiments were created. Temperature feedback was to be provided by an LM34 Precision Fahrenheit Temperature Sensor (TI, 2016).

3.8 Pumping and Recirculation

As mentioned in Section 3.5, the cold plate was designed to collect condensed isopropyl alcohol into one area so it could be recirculated and reused, minimizing waste of resources caused by potential leaks in the chamber seals. A peristaltic pump was chosen for this purpose because they keep the pumped fluid isolated from the actual motor and surroundings and are able to pump even when gases are trapped inside the piping (Burke, A., 2018). Because isopropyl alcohol can be corrosive due to the presence of water and other contaminants, it was desired to avoid direct contact with any sensitive mechanical or electrical components. The tubing used in peristaltic pumps is flexible and is compressed by a rotating roller head to push fluid in one direction, allowing the fluid to remain separate from the outside environment and motor. A sample graphic of a peristaltic pump is shown in Figure 15 below.

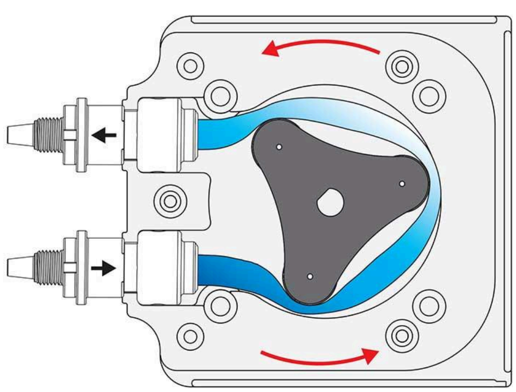


Fig. 15: Example peristaltic pump showing the direction of flow, inlet, outlet, and deformation of the flexible tubing (Burke, A., 2018).

In addition, although about 100 mL of isopropyl may be placed into the reservoir for operating the cloud chamber, only a fraction of that will be evaporating or condensing at any given moment. There will be a relatively low volume of isopropyl alcohol to collect and recirculate, so a pump mechanism that pulls isopropyl alcohol from the collection point will have a large volume of air mixed in with any alcohol sucked out. Unlike some other pump designs, the peristaltic pump is still able to effectively transport a mixture of gas and liquid because of the flexible tubing.

Initially, a flexible and chemically resistant tubing was designed to be inserted through the chamber wall and pump any collected alcohol to a larger external replenishment tank. The tank would be connected with another pump that would deposit recycled alcohol back into the reservoir. Once a fluid level detector in the reservoir signaled that the alcohol volume was running low, the pumps would activate to only refill the reservoir when needed to avoid wasting power and creating air circulation in the chamber that would disrupt condensation and reduce the saturation in the air. The pump connecting the chamber to the replenishment tank would have air in it that would escape once it entered the tank. Then, the pump connecting the tank back to the reservoir would be able to pump alcohol free from air bubbles into the reservoir, allowing for more efficient pumping and reduced chance of unwanted air circulation.

Unfortunately, due to time constraints, the pumping and recirculation system was not implemented. However, the modular nature of the chamber and location of all pumping equipment outside the chamber would allow for a fairly straightforward implementation of this system.

3.9 Lighting

In order to illuminate the cloud chamber and make particle trails visible, a strong white LED strip was used. The LED strip selected was the iNextStation Neon LED Strip Lights, shining a bright white light. The LED strip was cut into four pieces and was designed to rest on the perimeter of the cold plate, shining inwards near the bottom of the chamber (since that is where particle trails would be most likely to appear). The LEDs took in 12V power, with no controls necessary, and were integrated into the motor control breadboard (see Section 4.5). An image of the LED strips used is shown in Figure 16 below.

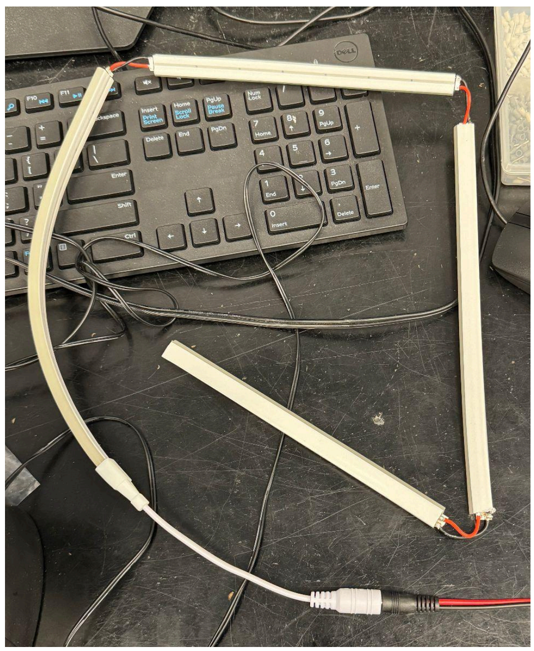


Fig. 16: LED strips (created by authors).

4. Clock Mechanism Design

4.1 Chamber Constraints

The primary constraint on the design and construction of the clock was the physical size of the cold plate on which the cloud chamber rested. The clock was constrained to an area of

8.625 x 7.125 inches to stay within the walls of the chamber. In addition to the geometric constraints for the clock design, the challenge of managing the containment of the alcohol vapors necessary for generating the cloud chamber effect also played a role in the clock design. To ensure the vapors would not escape and to protect electrical components from degradation in alcohol, a system was developed to transmit motion and electrical wires through the chamber walls while limiting the areas for vapor to escape. All these constraints played a significant role in the initial brainstorming phase all the way to the final design of the clock.

4.2 Clock System Design

In brainstorming the clock system, many different ideas were generated for consideration. The most ambitious initial design idea was to manipulate the direction of flow of the radioactive particles visible in the cloud chamber to illuminate the time in either an analog or digital clock form. This idea would have used radioactive specimens to ensure the constant generation of visible particles and a mechanical system in place to manipulate their direction and orientation depending on the current time. This idea was thrown out rather quickly due to the complexity of the proposed design given the amount of time allotted for this project.

The second general concept for the clock involved two ring gears in the center of the chamber with cantilevered hands to display the time in analog form. These rings would be cut from continuous cast acrylic using an industrial laser cutter. The rings would allow the radioactive particles to be visualized in the center of the clock as an aesthetic decision. Unlike a traditional analog clock, the cantilevered hands would be directed inwards towards a “central” point to improve visibility of the bottom of the cloud chamber and allow for easier condensation.

However, the method of transmitting the rotational motion from a motor outside of the chamber to these inner rings presented a challenge and required several different ideas to be suggested.

The initial idea to solve this transmission problem involved one stepper motor placed outside the chamber rotating the clock hands via gears that would mate through a slot in the side of the wall. The gears and motor would be close to the face of the cold plate and simply rest on the side of the compressor-cooled ice cream machine. This idea was rejected due to the difficulties of sealing the gap in the chamber wall to contain alcohol vapor. A second idea involved using a latex-like membrane and a gear rack to transmit motion without breaking the seal of the chamber. This idea was rejected because of complications in acquiring and installing a membrane that would competently seal the chamber while also conveying a precise motion through to the ring gears. Two other more inventive ideas involved the use of magnetic forces and hydraulic motion to rotate the clock hand rings. These ideas were rejected for the complexity involved in their potential design.

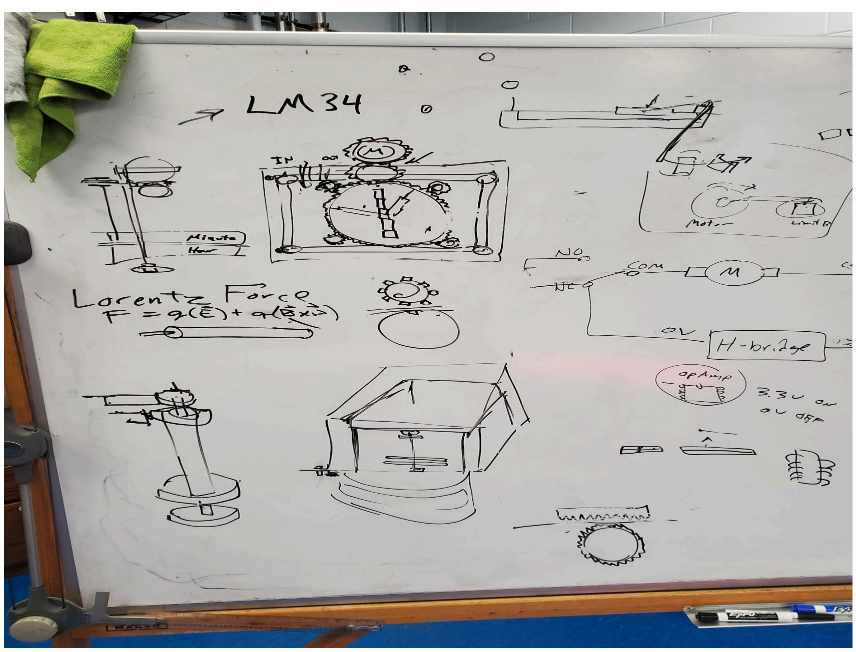


Fig. 17: A whiteboard image with early sketches of all of the brainstormed ideas (created by authors).

The last and ultimately final design considered for clock rotation was the use of vertical shafts to transmit the motion through the top of the chamber. This design would allow the easy sealing of the shaft using a silicone ring and a simple mechanism for transmitting motion from an external motor to the internal clock rings.

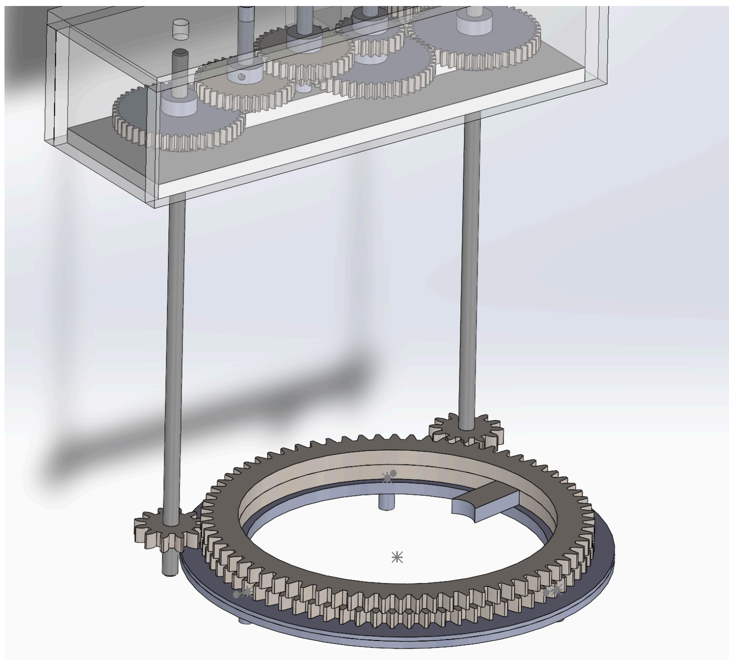


Fig. 18: SOLIDWORKS model of clock assembly depicting method of transmitting motor rotation vertically to clock ring gears (created by authors).

The gears themselves went under several iterations as different methods of manufacturing were discussed. Initially, the research surrounding acrylic in the presence of alcohol led to the selection of aluminum gears since it was believed acrylic would crack and degrade. This meant the aluminum gears would need to be cut using a CNC mill, requiring the teeth size to be large enough to allow a 1/8th inch milling bit to cut in between each tooth accurately. As further research and experimentation revealed no significant degradation for acrylic under alcohol, the gears were moved back to an acrylic model, allowing for more precise machining.

The final diametral pitch of 12 was maintained with the acrylic gears. This diametral pitch allowed for ring gears with 72 teeth, making the pitch diameter six inches. This choice was made to optimize the amount of space in the center of the ring, allowing the most area for subatomic particles to be viewed from the clock hands. This pitch diameter maximized the size of the gear that could fit within the walls of the chamber.

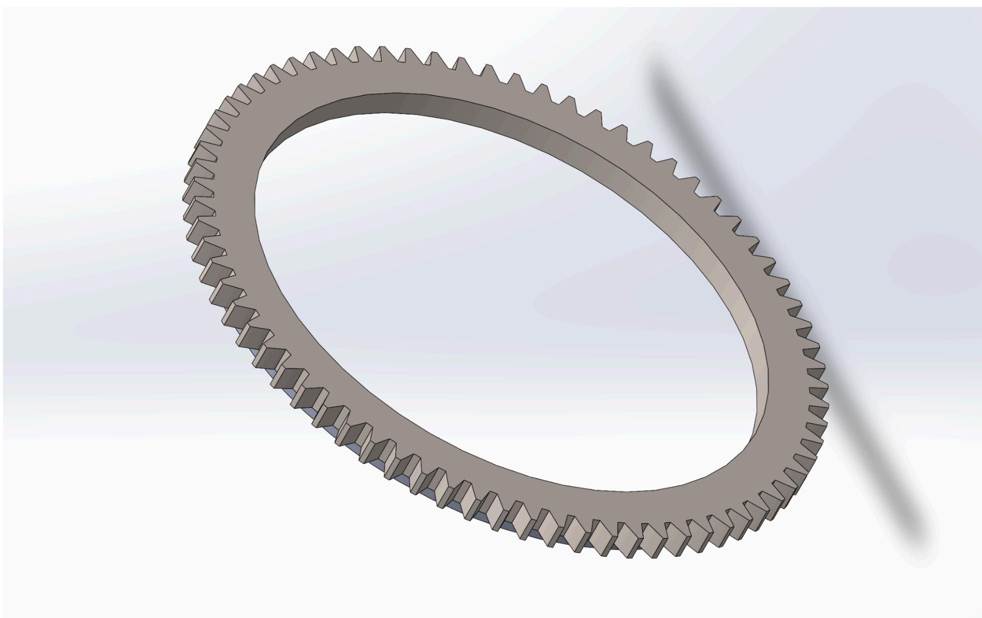


Fig. 19: Final model of the minute hand ring gear

Once the final design of ring gears with clock hands cantilevered from the sides was settled, a finite element analysis was run on the rings. Using the estimated weight of thorium TIG welding electrodes, discussed in Section 4.3, an analysis was run using SOLIDWORKS simulation software to determine the likelihood of mechanical failure.

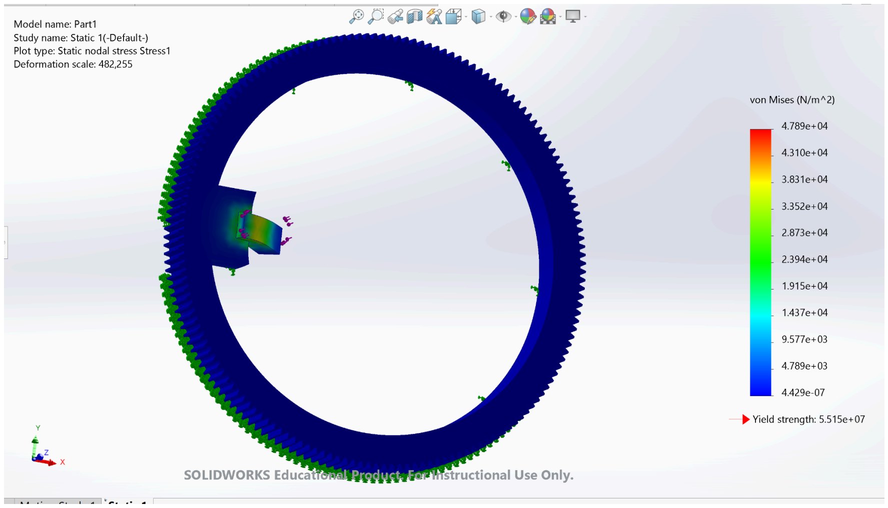


Fig. 20: Finite element analysis of early model of clock hand ring gear. Early model used different diametral pitch and several more teeth but maintained a pitch diameter of six inches.

As can be seen from the image above, the acrylic ring would experience stresses several orders of magnitude below the yield strength of the material. This test allowed designing to continue without any worry to the physical loads and material properties of the construction under stress. Even though this ring design was not the final iteration, this early result made future studies unnecessary.

The driver gears were selected to be one inch in pitch diameter to fit within the confines of the chamber. They also needed to be the same diametral pitch as the ring gears so as to mate properly and transmit rotation correctly. These driver gears were attached to aluminum shafts at designated heights to fully mate with the ring gears and allow for rotation transmission through the chamber. Also, all gears used in this clock assembly and gear train used a pitch angle of 20 degrees since the angle of 20 degrees increases tooth strength and load-carrying capacity (Wikipedia, n.d.).

The shafts used to transmit the motion through the chamber walls were selected to be aluminum 6061 with a diameter of ¼ inch. These metal shafts were researched and understood to have no negative reactions with isopropyl alcohol. The shafts would rest on the surface of the cold plate and rotate with minimal friction due to alcohol pooling on the plate.

4.3 Clock Hands

The hands of the clock were attached to two ring gears placed on the face of the cold plate. These ring gears were mounted on a stationary ring that would be elevated just above the plate by three small legs. This stationary ring was designed with a slight indent on the underside to allow for the attachment of the ring LED that would display the seconds of the clock. On the top side of this stationary ring, a 1/10th inch thickness ring was cut from acrylic and glued to the top of the stationary ring. This method was repeated at different diameters for each ring gear to minimize the frictional surface area of the gears. Additionally, by using thin rings of similar diameters, these alignment rings also maintained the positioning of the ring gears, keeping them from sliding off one another. A section view showing the mating of the ring gears is shown in Figure 21 below. Tolerances are included in the design but not visible in the image due to the resolution.

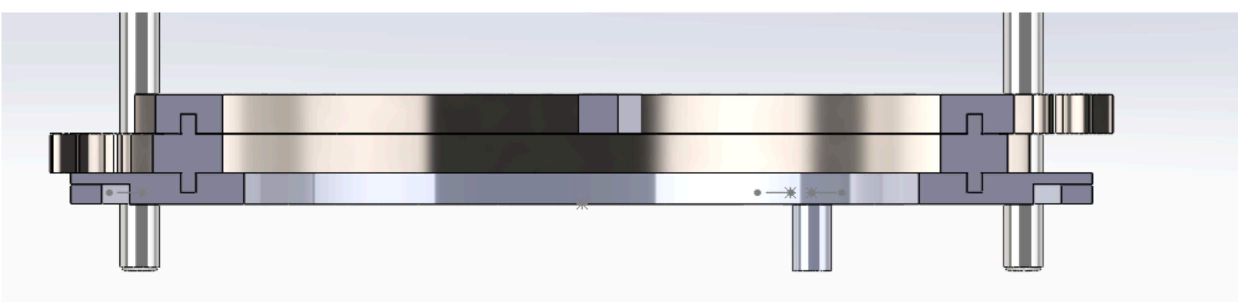


Fig. 21: Ring gear assembly with the minute hand gear on top, hour hand below, and stationary ring on the bottom. The ring LED is mounted to the bottommost and outermost portion of the stationary ring. Both ring gear driver shafts but only one support leg are visible in this figure (created by authors).

Once the problem of overcoming friction was solved, the next challenge was to determine the form and mechanism of the clock hands themselves. The initial idea was to use 2% thoriated TIG welding electrodes as hands so as to emit a greater density of visible alpha and beta particles in the center of the clock. These electrodes would be attached via a clamping mechanism on top of the side of the minute hand or top ring gear and on top of an acrylic arm jutting out from the hour hand or bottom ring gear. Due to time constraints, these thorium-based hands were never constructed or added to the clock. Instead, white acrylic hands were cut to be attached with acrylic glue to the inside of the blue ring gears.

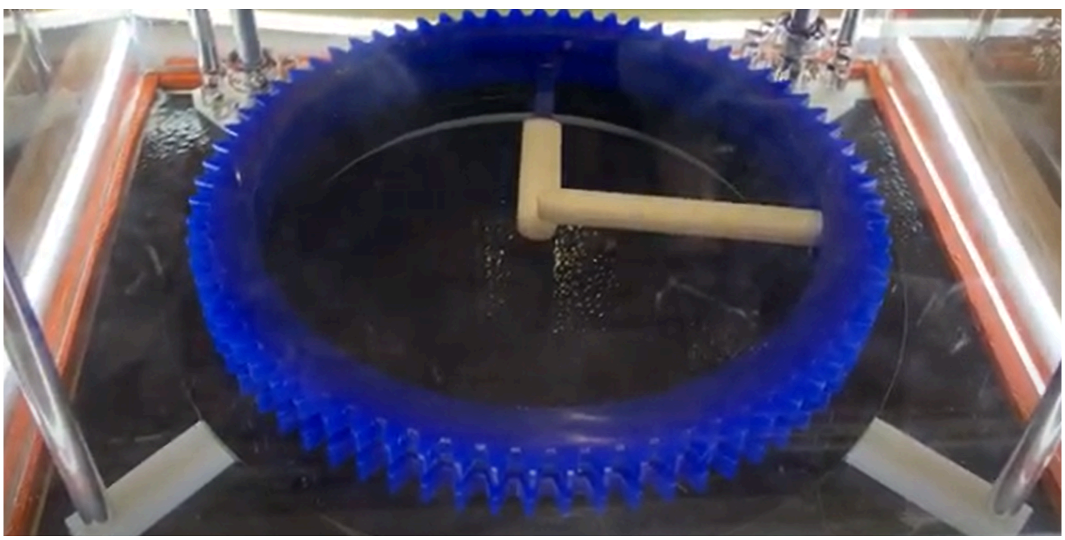


Fig. 22: An image of the final prototype with the white acrylic hands extending from the blue acrylic ring gears (created by authors).

4.4 Gear Train

Initially, the clock mechanism was intended to use two separate stepper motors to turn the two ring gears. This idea was altered slightly to use just one stepper motor for a couple reasons. One of the reasons was to retain precision for the hour hand gear. Since the hour hand gear would turn at such a slow rate, there was concern over how precise a stepper motor would be at that speed. The other reason was the interest in proposing a complex design challenge of creating a gear train that would be able to step down the rotational speed of the minute hand to the hour hand. The added bonus of making this gear train was the educational objective of this project could be met with an educational demonstration of gears as well as the demonstration of a cloud chamber.

The early design of the gear train relied on the constraints of size and the interest in stepping down to a precise speed. From the beginning of the design, the diametral pitch was selected to be 24 since the small tooth size generated allowed for more precise rotation and accuracy. The gear train needed a high level of precision since the hour hand relied on this rotation being transmitted correctly. Additionally, this gear train needed to result in a rotational speed 1/12th of the speed of the first gear. Initial calculations were conducted to get a sense for scale of gears in the gear train and then the sizes were finalized and confirmed using GearGenerator.com.

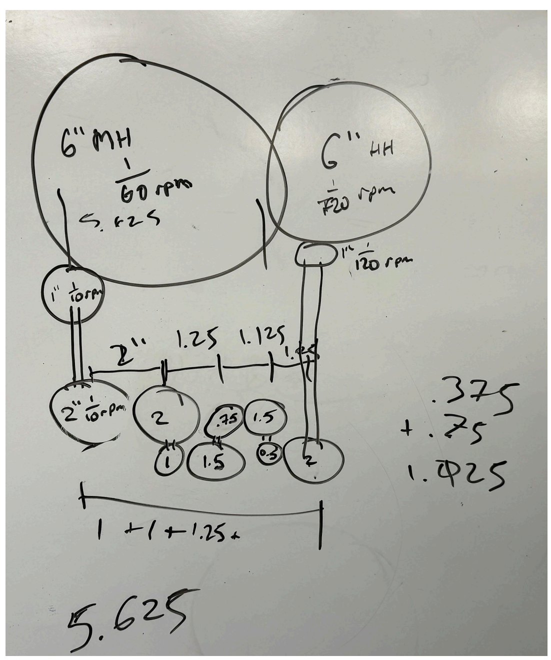


Fig. 23: Hand calculations of both gear sizes and overall gear train length (created by authors).

The gear train was finalized using iterations from GearGenerator.com which allowed for multiple different gear sizes and connection types to evaluate the speed reduction of the gear train. Below is a figure showing the final gear train in the simulation.

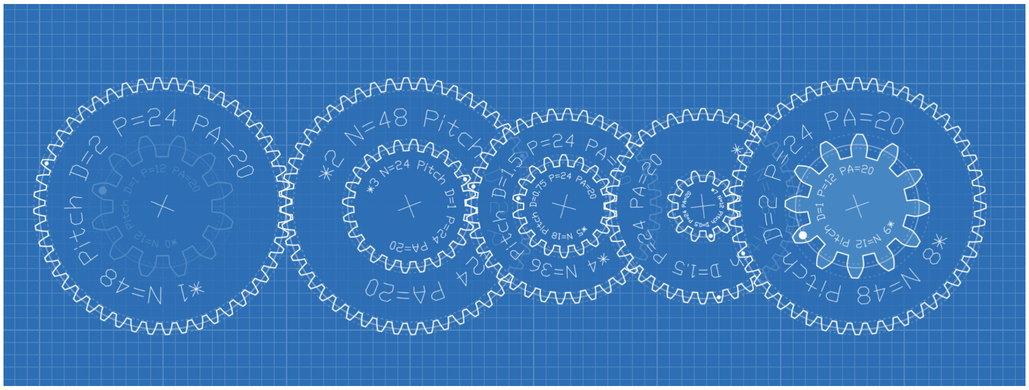


Fig. 24: Image of the final gear train design modeled in GearGenerator.com with relevant gear parameters shown on each gear (created by authors).

Once this design was finalized, the shafts responsible for driving the ring gears were aligned with the ends of the gear train. Using set screws and acrylic ring attachments, these gears were clamped onto the shafts to ensure transmission from the gear rotation to the shaft. As for the gear box, several different designs were considered for the housing of the gear train. An early design opted to have the sides of the container close to the edges of the gears.

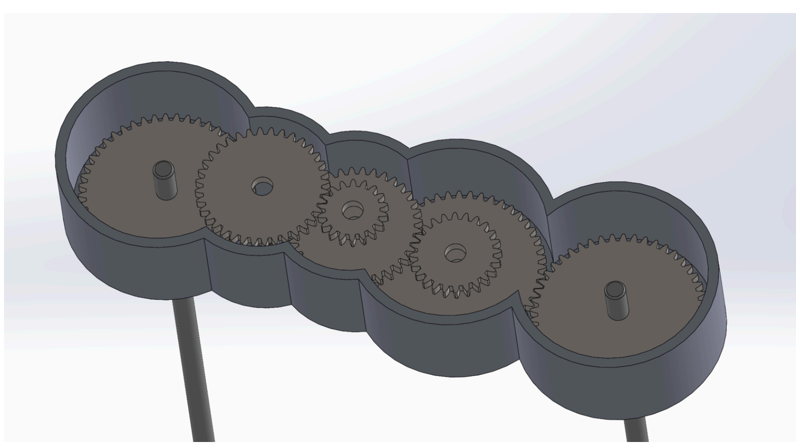


Fig. 25: Early gearbox design concept with walls close to gears (created by authors).

The complexity of this design would require the use of 3D printers which would have brought a different aesthetic to the clock. Additionally, the material would not allow viewers to observe the gear train during operation. Given that one of the primary goals of this project was to design a piece of art and an educational demonstration, the design shifted to using clear acrylic pieces in a more rectangular design. The final model shows the set screws and motor all attached to a rectangular gearbox made from clear acrylic.

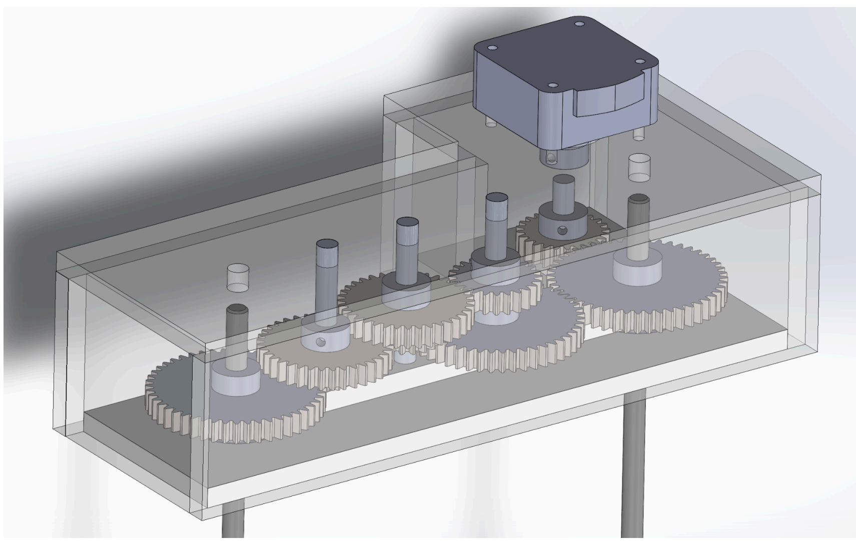


Fig. 26: Final SOLIDWORKS model for the gearbox and gear train (created by authors).

The walls of the gearbox were cut using the industrial laser cutter and then the pieces were glued together using acrylic glue. Due to the slight angle the laser cutter used to cut out the pieces, there was a slight offset in the final box since the pieces had non perpendicular edges. Despite the slight manufacturing errors, the gearbox retained its function and held the gear train in place during clock operation.

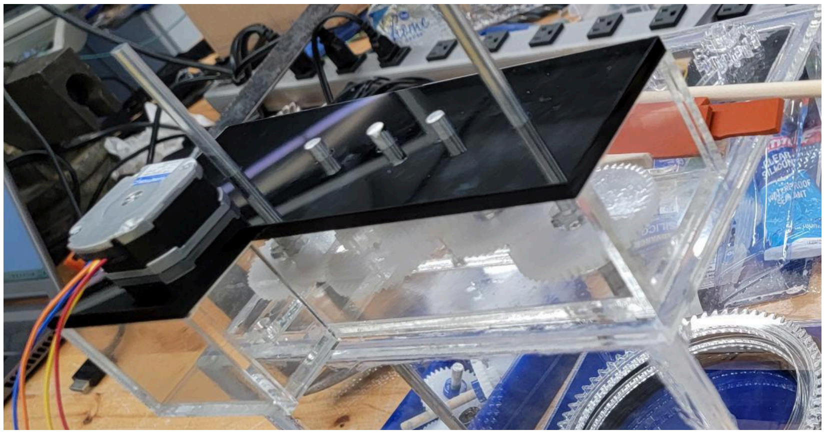


Fig. 27: Image of the final gearbox with clear acrylic walls (created by authors).

At each end of the gearbox, there were holes for the driver shafts to extend vertically through both the box and the chamber top. These holes were necessary for transmission of rotation to the driver gears, but they presented a problem with the sealant of the chamber to prevent vapors from escaping. To solve this problem, silicone rings were created using a 3D printed mold and Ecoflex 0030 silicone. These rings were cast with a clearance just under the diameter of the shaft, 0.24 inches, to ensure a complete seal. The seal rings would sit just on top of the chamber wall, fully sealing the rotation of the shaft.

Fig. 28: Image of silicone seal ring with 3D printed mold

4.5 Motor Control

Due to the gear train design, only a single motor was required. A Sanyo pancake bipolar stepper motor was selected to drive the gear train. The NEMA 17 size and pancake shape allowed for simple implementation into the design. The motor was capable of 1.8° steps (200 steps/revolution) and a holding torque of 26 oz-in, but required that current be limited to 1A. The motor used a typical four-lead bipolar stepper motor wiring scheme as seen in the figure below (Pololu, n.d.a).

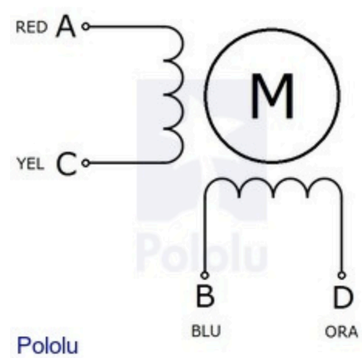


Fig. 29: Wiring diagram for the Sanyo pancake stepper motor

A MP6500 Stepper Motor Driver Breakout Board was selected to drive the motor. This chip allowed for current to be limited to 1A and included microstepping functionality. The chip also included a sleep condition to cease providing power to the motor which allowed for decreased power consumption and prevented the motor from overheating. See the figure below for the pin layout (Pololu, n.d.b).

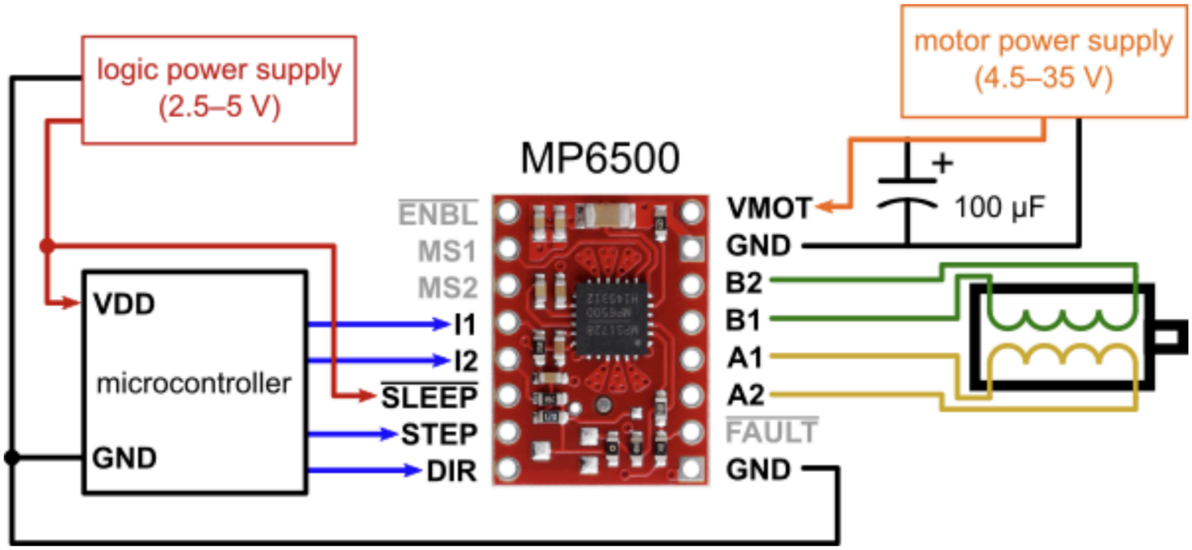


Fig. 30: Basic wiring diagram for connecting a microcontroller to the MP6500 Stepper Motor Driver Breakout Board

12V was used to power the motor, and a voltage regulator stepped the voltage down to 5V for logic. This simple power usage required only a 12VDC 2.5A power supply that could be plugged into a wall outlet. An Arduino Nano was used as the microcontroller for the system.

The circuit was simple to construct, as few components were required. As mentioned previously, all voltages were 12V or 5V and were supplied by a single source. A 100µF electrolytic capacitor was wired between 12V and ground to protect the chip internals from voltage spikes. Current was limited to 1A by grounding I1 and connecting I2 to high impedance (I2 was left unconnected to achieve this). Only full 1.8° steps were used, so both MS1 and MS2 were connected to ground. The motor leads were arranged such that B2 was connected to the blue wire. This arrangement allowed for clockwise rotation. The $\overline{SLEEP}$ and STEP pins were connected to the Arduino. See the figure below for the circuit diagram.

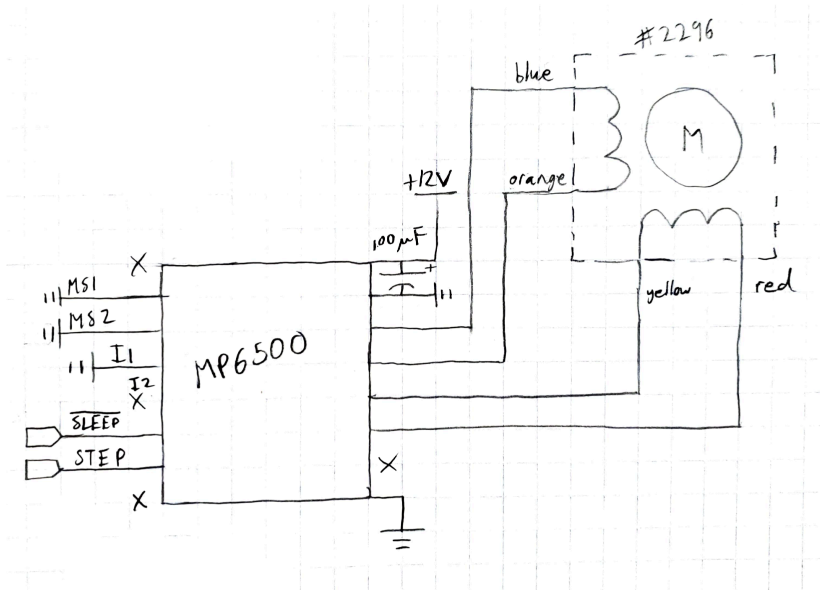


Fig. 31: Circuit diagram of the motor control system (created by authors).

The gear ratio between the minute hand and the motor was 12:1, so for every 6° the minute hand rotated (one minute or 1/60th of 360°) the motor rotated 72° (40 1.8° steps). This rotation was transmitted through the gear train to rotate the hour hand 0.5° (1/60th of an hour or 1/720th of 360°). The Step pin on the MP6500 receives a pulse input and causes the driver to output a single step on the motor. Therefore, the Arduino was programmed to send 40 pulses to step the motor 40 times each minute. When testing the program it was found that 25ms delays between and during pulses were sufficient to step the motor correctly, in addition to two 100ms delays within the program. To account for these delays, the Arduino would wait for 57799ms and then signal the 40 steps. Once the 40 steps were completed, the minute was over and the Arduino would wait again. During the waiting period, the Arduino set the $\overline{SLEEP}$ pin to low (0V) to put the MP6500 chip to sleep and prevent the motor from actively holding position.

For demonstration purposes, a second mode was created for the clock. This mode would consist of continuous rotation around the clock in order to demonstrate the gear ratios much faster. A switch was added to the circuit to signal the Arduino to switch modes (Fig. X). The switch would either draw the D5 input pin high by receiving the 3.3V signal from the other side of the board or bring it low using the pulldown resistor to ground. Depending on the input pin D5 received, the motor would enter either clock mode or demo mode.

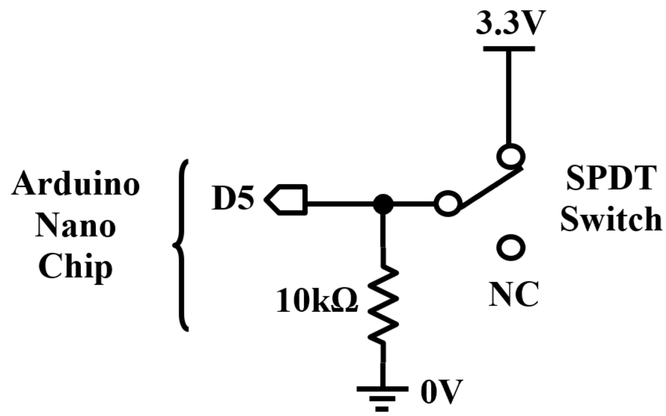


Fig. 32: Simple image of the mode switch circuit (created by authors).

The demo code used the same 25ms pulses and delays with none of the waiting periods. This resulted in continuous rotation of the minute and hour hands at 0.5 rpm and 0.042 rpm, respectively. The demo code was integrated into the main program (Appendix). Due to the heat generated by the motor, the demo code was only used for short demonstrations.

5. Final Physical Design

Sections 3 and 4 described designs of various parts and assemblies of the cloud chamber clock. However, due to time constraints, not all systems were able to be implemented (such as the heating elements and recirculation system). Figure 33 below shows views of the front and back of the full final assembly.

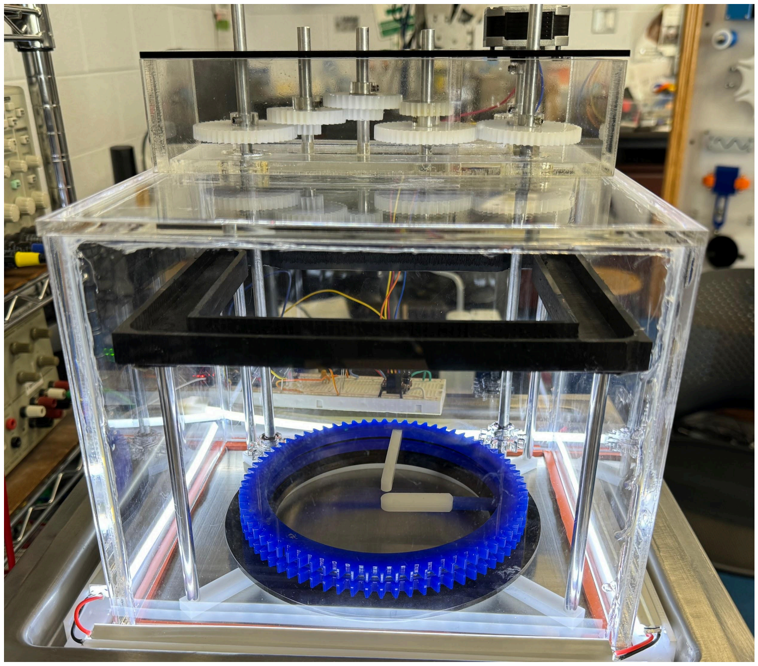


Fig. 33: Front view of final assembly (created by authors).

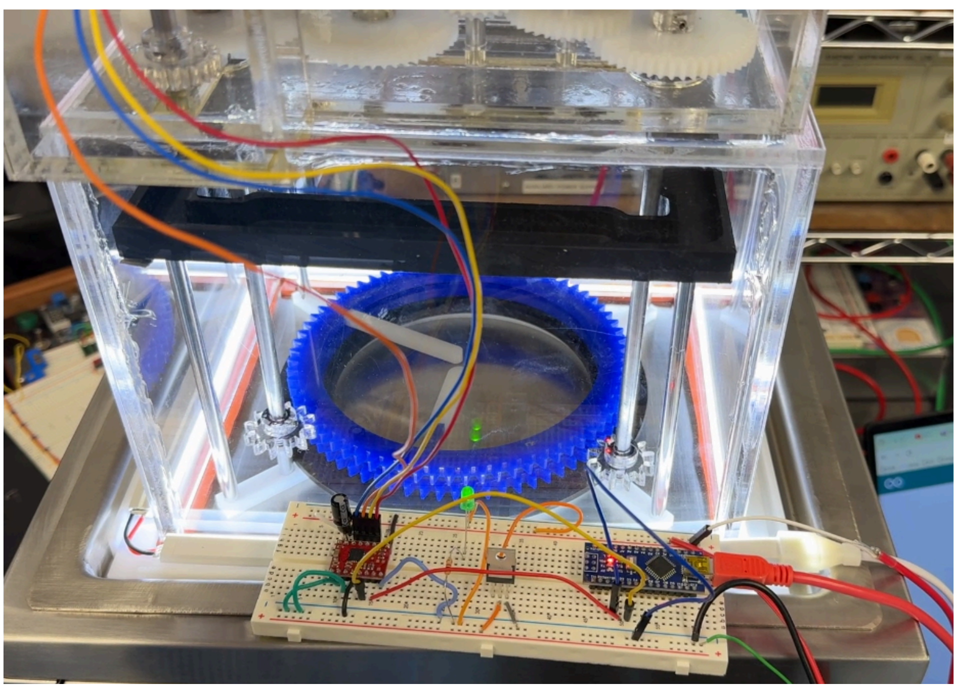


Fig. 34: Rear view of the final assembly, showing the breadboard circuitry and Arduino Nano controlling the motor (created by authors).

The final assembly did not have a cold plate due to time constraints preventing it from being machined. However, a temporary alignment tool was created from laser-cut acrylic, shown in Figure 35 below and visible in Figure 33 and 34 above.

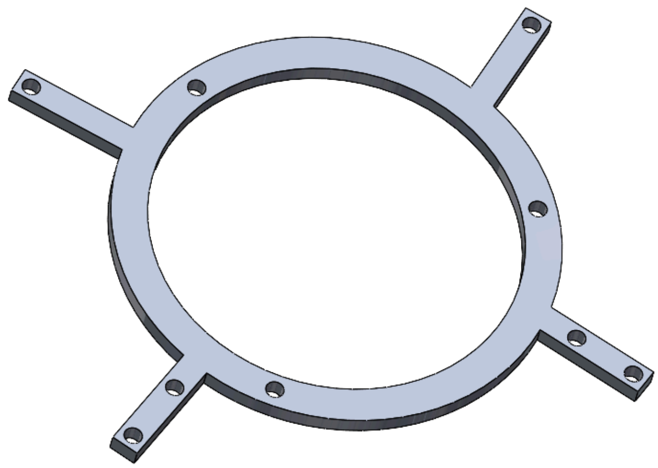


Fig. 35: Temporary cold plate replacement and shaft and leg alignment tool (created by authors).

This tool allows all legs and shafts to still be properly aligned, with holes being positioned in the exact spots located on the cold plate. The center and sides are left open so the ice cream machine compressor table would be exposed to the air, allowing a temperature gradient to still form. If the tool was a solid acrylic sheet, the bottom of the chamber itself would not be cold enough to encourage significant condensation due to the added thermal insulation.

The bottom of the chamber was covered with black tape to improve visibility of particle tracks. However, no alcohol vapor mist formed and particle trails were not visible, likely because of the absence of heating elements (described in Section 6). While the cloud chamber itself did not function properly, the clock portion was fully operational and performed successfully.

6. Future Improvements

There are multiple opportunities for future improvements to this project. The first is to design and implement the heating system. As stated previously (Section 3.7), delays in creating the cloud chamber prevented any prototype designs for the heating system. The lack of a heating system is a likely source for why the final cloud chamber failed. Without added heat forcing alcohol evaporation and increasing the temperature gradient, the vapor likely never reached saturation, and thus could not become supersaturated in the lower, cooler part of the cloud chamber. Implementing a heating system in the future would likely create a working cloud chamber. Additionally, the sealant of the chamber was rushed and not entirely proven making it hard to determine whether the conditions were correct for the cloud chamber effect. If given more time, pressure testings could be executed to ensure proper sealant of the chamber, ensuring the conditions would be met for cloud chamber activity.

The second possible improvement would be to improve the gear manufacturing. Laser-cut acrylic allowed for rapid prototyping of the gear train, but the gears were created with some flaws. The gears were cut at an angle due to the disparity in heat concentration from the top of the material to the bottom (cutlasercut.com, 2023). Creating the gears in a more precise manner, such as on a CNC machine out of metal, would likely improve the performance of the gear train.

Another opportunity for future improvement would be to implement the alcohol recirculation system. As explained previously (Sections 3.5, 3.6, and 3.8), large portions of the proposed recirculation system have been designed. The elevated reservoir and the collection ramps on the cold plate were designed and the reservoir was manufactured for the final demonstration. Additionally, a peristaltic pump was obtained for later implementation.

Implementing these features would allow for the chamber to be filled with alcohol once and then again only when necessary. This change would move the project closer to being a permanent installation.

The final opportunity for future improvement would be to design a system in which the cloud chamber is periodically turned on and then off. The goal would be for the chamber demonstration to function similar to a striking clock or a cuckoo clock by turning on the cloud chamber at a certain part of the day, perhaps at noon. To avoid tampering with the internals of the ice cream machine, this would likely be achieved by creating an external actuator to turn the machine's power switch on and off. All of the described improvements would enhance the project's value as a permanent installation and educational demonstration.

7. Conclusion

The cloud chamber clock was not fully complete at the time of the course's conclusion. All major systems were in place, but designs (like the cold plate and heating elements) were unrealized in reality primarily due to time constraints. However, the clock functioned successfully and was very robust, with seamless switching between the clock and demo modes. The clock was able to be set by hand as desired if adjustments were needed. The build quality remained that of a prototype, with more durable glass wall, aluminum gears, and thoriated tungsten electrode clock hands not implemented, but the project was still considered a success.

The creation of a clock within a cloud chamber has never been done before, and the authors knew this project would be an ambitious one. While many design improvements could be made, the success of the reusable, modular, and functional clock design fulfilled the major objectives. The authors learned many lessons throughout the process, such as design for manufacturability and learning what is practical or cost-effective. Production issues such as improperly cut gears forced quick design changes and imperfect solutions, but taught valuable lessons of manufacturability and adapting quickly as needed. Perhaps most importantly, the authors learned not to become too prideful and ambitious in the engineering process.

With a few improvements described in Section 6, future groups could fully flesh out a more permanent, durable, and visually appealing design of the cloud chamber clock, allowing the University to use this project as a science demonstration for years to come.

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9. Appendix

Arduino Motor Driver Code

```
//Defining Pins For Motor Use
#define motorStep 2
#define motorSleep 3
#define controlPin 5

void setup() {
  // put your setup code here, to run once:
  pinMode(motorStep, OUTPUT);
  pinMode(motorSleep, OUTPUT);
  digitalWrite(motorSleep, HIGH);
  digitalWrite(motorStep, LOW);
  pinMode(controlPin, INPUT);
}
  // put your main code here, to run repeatedly:
void loop() {
  if (digitalRead(controlPin) == HIGH) {
    digitalWrite(motorSleep, HIGH);
    delay(100);
  //For Loop that moves clock to next minute position
    for (int i = 1; i <=40; i++) {
      digitalWrite(motorStep, HIGH);
      delay(25);
      digitalWrite(motorStep, LOW);
      delay(25);
    }
    delay(100);
    digitalWrite(motorSleep, LOW);
    //Delay code for minute pause between rotations, 8257 * 7 ms gets to 57799 ms which is the amount needed to pulse every minute
    //Also checking to see if switch has been flipped into demo mode
    for (int j = 1; j <= 8258; j++) {
      if (digitalRead(controlPin) == LOW) {
        break;
      }
      else {
        delay(7);
      }
    }
  }
  else {
    //Demo code to show clock moving without sleeping
    //Allows audience to see motor moving on demand, should only run for short amount of time due to overheating
    digitalWrite(motorSleep, HIGH);
    digitalWrite(motorStep, HIGH);
    delay(25);
    digitalWrite(motorStep, LOW);
    delay(25);
  }
}
```