“Polarizing ^{3}He Gas”

Senior Physics Research
Tamara Beth Hayford
Dr. Todd Averett, Advisor

Abstract

This research project entailed building a target system in which it would be possible to polarize ^{3}He gas so that the polarized ^{3}He can be used to study the neutron at Jefferson Lab. Involved in this process was the design and construction of a high-temperature oven, the construction of a coil system, the construction of an NMR system, and the construction of a laser and optics setup. At the end of the year, there was a successful polarization of ^{3}He in a target cell. Further understanding of the cell fill process was also achieved through the filling of another ^{3}He target cell.

1. Introduction

The main purpose of this research was to build a lab in which it is possible polarize helium-3 (^{3}He) using optical pumping and spin exchange. There are currently 2 labs in which ^{3}He target material is optically pumped and polarized in aluminosilicate glass cells that are then used at Jefferson Lab: The College of William and Mary and University of Virginia. The motivation for polarizing ^{3}He is that there is an unpaired neutron in the polarized ^{3}He nucleus, which approximates a polarized neutron. Thus, at Jefferson lab, an electron beam can be sent through the polarized ^{3}He gas in order to study the neutron. Currently approved experiments at Jefferson Lab that involve polarized ^{3}He include: Experiment E94-010, Measurement of the Neutron (^{3}He) Spin Structure Function at Low Q^2: A Connection Between the Bjorken and Drell Hearn Gerasimov Sum Rules; Experiment E95-001, Precise Measurement of the Transverse Asymmetry A_T in Quasi-

Elastic Electron Scattering from ^{3}He at low Q^2; and Experiment E99-117, Precision Measurement of the Neutron Asymmetry A_1^n at Large x using CEBAF at 6 GeV. [1] The ability to approximate a polarized neutron is important because it is not possible to study free neutrons; free neutrons are unstable and have a short lifetime that is on the order of ten minutes. [2] A few of the potential applications of polarized ^{3}He are: experiments in medium and high energy physics, polarization of thermal and epithermal neutron beams from reactors and spallation sources, and magnetic resonance imaging of the lung with the use of inhaled hyper-polarized ^{3}He gas. [3]

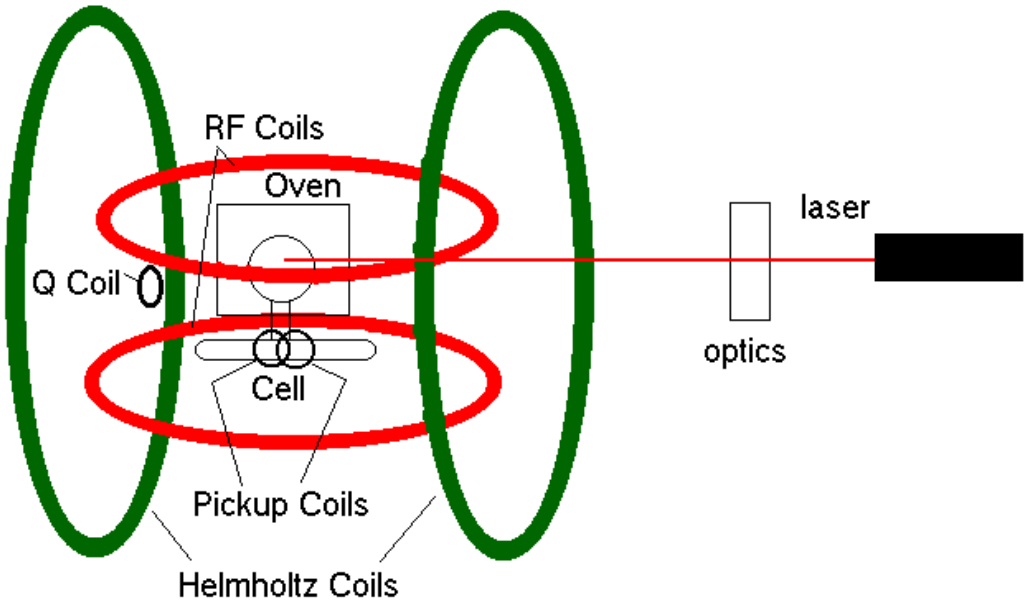

Figure I: Schematic drawing of a ^{3}He polarizing target system. Generally speaking, this system involves a coil system, an oven system, a cell, and a laser and optics system. The coil system involves two Helmholtz coils, two RF coils, two pickup coils, a Q coil, an oven, and a glass target cell.

Figure I above shows a schematic drawing of a ^{3}He polarizing target system. Generally speaking, this system involves a coil system, an oven system, a cell, and a laser and optics system. The coil system is made up of two large Helmholtz coils, two smaller RF coils, each with four turns of wire, two small pick-up coils, each of 100 turns of wire, and a Q-coil, which has 200 turns of wire. The coils within a pair are parallel to each other, and the three pairs of coils are perpendicular to each other. The Helmoltz coils and the RF coils are outside of the oven system, while the pick-up coils are on either side of the lower chamber of the cell. The Q-coil is attached to one of the posts that holds the Helmholtz coils in place, and it is parallel to the pick-up coils. The oven system involves a Teflon oven that encloses the upper chamber of the cell in order to vaporize the rubidium (Rb) inside it, an oven controller that uses a resistance temperature device (RTD) to measure the temperature inside the oven and then determines how to respond with the heaters, and two heating units that heat an air flow which then continues into the oven. There is a tube that comes out of the top of the oven to allow air to leave the oven as more comes in. The cell has two chambers and is made of aluminosilicate glass. The laser and optics set up includes a 30 Watt diode laser that emits laser light of 795nm, a lens of focal length 7.6 cm, a polarizing beam splitter cube, three quarter wave plates, and two mirrors. This lab was built by two undergraduate students: Daniel Milke and Tamara Hayford, under the guidance of Dr. Todd Averett. Daniel Milke was responsible for the NMR system and the computer programming, and Tamara Hayford was responsible for the oven design and construction, the oven controller, and the laser and optics set-up.

2. The Target Cell

The target cell is made of blown aluminosilicate glass. A schematic drawing of the cell can be found in Figure II. This type of glass is used because it has a low porosity to ^{3}He, which makes it a good container for ^{3}He gas. It is important that the glass is as smooth as possible in order to prevent the ^{3}He atoms from interacting with impurities in the cell walls. There are a variety of techniques that are utilized to prevent interaction between the cell walls and the ^{3}He nuclei such as treating the glass with nitric acid cleaning and resizing the glass. These treatments remove surface contamination and prevent micro fissures and impurities in the glass. [4] The cell has two chambers; the upper chamber is spherical with a radius of approximately 2.5 inches, and the lower chamber is oblong with a length of approximately 40 cm and a radius of approximately 0.75 inches. The radius of the ends of the lower chamber is approximately 1 cm. The thickness of the glass at these ends is about 100 micrometers. [5] The thickness has to be minimal in order to prevent interactions between the glass and the electron beam during experiments at Jefferson Lab. The upper chamber contains ^{3}He, nitrogen (N_2), and Rb. It has a lip that is in place to prevent Rb from dripping into the lower chamber while it is still in its liquid state. There is a transfer tube between the two chambers that is of approximate radius 0.25 cm and approximate length 6 cm. The bottom chamber ideally contains ^{3}He and N_2, though it is nearly inevitable that at least a mono-atomic layer of Rb will be present in the lower chamber. One of the purposes for having a dual-chambered cell is that Jefferson Lab is using these cells to study the neutron, and Rb would contaminate the results of Jefferson Lab experiments were it in the same place that the electron beam is being sent through.

Since glass has a low thermal conductivity, the Rb is kept in the upper chamber by the heat differential between the upper chamber inside the oven and the lower chamber below the oven when the oven is on, and by the lip in the upper chamber when the cell is not being heated and the Rb is in a liquid or solid state. The ^{3}He can flow freely throughout the entire cell.

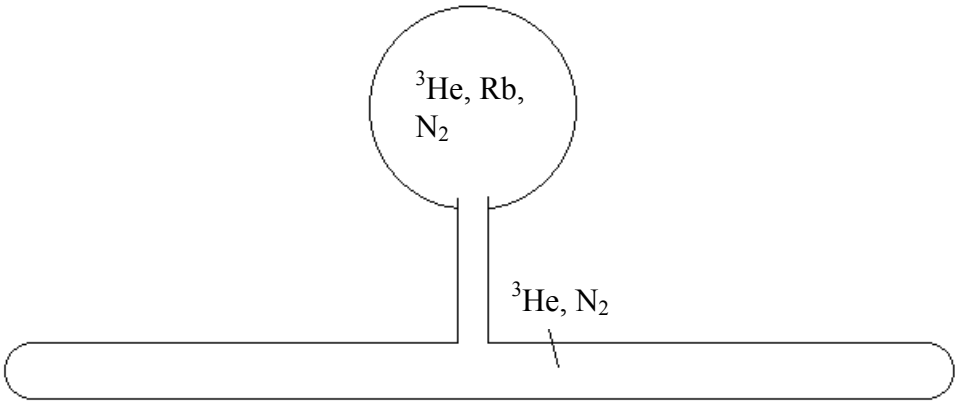

Figure II: The glass cell that contains the ^{3}He, N_2, and Rb target material. The Rb is only in the upper chamber, while the ^{3}He and N_2 move throughout the cell.

The cell is filled with 8.5 atm of ^{3}He (at room temperature), and a small amount of Rb, approximately 0.25 grams, is added in the upper chamber. A small amount of N_2 is put inside the cell, as well. The nucleus of ^{3}He is mainly in an S state with protons that are anti-parallel to each other. Thus, when the ^{3}He nucleus is polarized, the unpaired neutron approximates a polarized neutron. It is fairly easy to correct for the degree of polarization that is carried by the remainder of the nucleus. Rubidium has an atomic spin of ½, and it has one outer shell electron. The purpose of the Rb is for its outer shell electron to

polarize the ^{3}He nuclei. In order for the Rb to polarize the ^{3}He nucleus, it is initially vaporized by the oven, which is heated to 170 degrees Celsius. There is a magnetic field of 25 G, which is supplied by the Helmholtz coils. This magnetic field causes Zeeman splitting in the Rb electrons. The circularly polarized laser beam of wavelength 795nm and +1 spin projection is then directed at the oven so that it passes through the optical windows and the upper chamber of the target cell in order to polarize the Rb electrons. This process is called optical pumping. A diagram of the optical pumping process is shown in Figure III.[2] Only Rb electrons that are in a $5S_{½}$, m= -½ state can absorb this type of light. The electrons are excited into a $5P_{½}$, m= +½ state. At this point, the Rb electron decays to either its original state or the $5S_{½}$, m= +½ state. If it decays to its original state, it is again excited to the $5P_{½}$, m= +½ state, where it will again fall to one of the two lower states. Since only the $5S_{½}$, m= -½ state electrons can absorb the laser light at 795nm, those that fall to the $5S_{½}$, m= +½ state remain there. Within seconds, all of the Rb electrons are collected into the $5S_{½}$, m= +½ state, making it polarized.

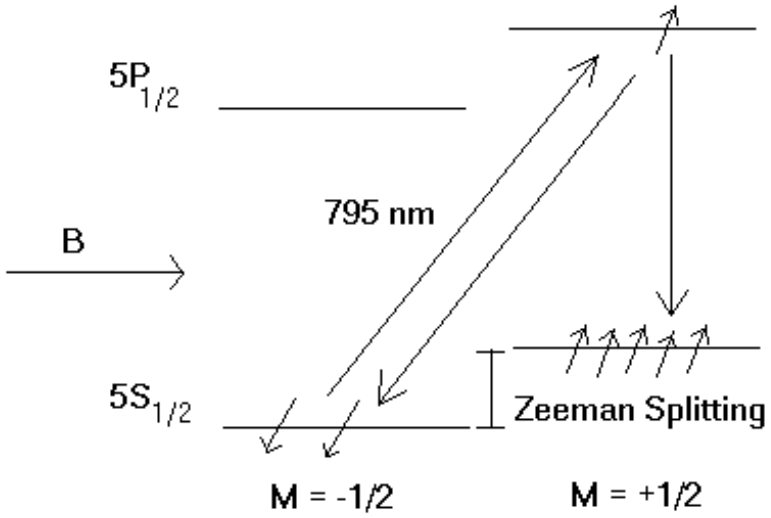

Figure III: The optical pumping process. As the magnetic field, B, is applied to the system, there is a zeeman splitting effect in the energy levels of the Rb electrons. Only those electrons in the $5S_{½}$, m= -½ state are able to absorb the laser light. When an electron absorbs the light, it is excited to the $5P_{½}$, m= +½ state, at which point it decays to either the $5S_{½}$, m= -½ state or the $5S_{½}$, m= +½ state. If it decays to the $5S_{½}$, m= -½ state, then it absorbs the laser light again, and the process repeats. Within seconds, all of the Rb electrons end up in the $5S_{½}$, m= +½ state.

Were there no other substances in the upper chamber, the excited Rb electrons would emit photons upon decaying to lower states. These photons would have the adverse effect of depolarizing the Rb gas. The N_2 gas prevents the emission of these photons by causing the Rb electrons to de-excite during collisions. When an excited Rb electron collides with an N_2 molecule, the N_2 molecule absorbs the energy released by the Rb electron as it decays. In order to prevent as many photons from being emitted as possible, a high enough density of gas is needed to ensure a large number of collisions. However, if the density of N_2 is too high, it will adversely affect the experiments run at Jefferson Lab

through interactions between the electron beam and the N_2. It has been experimentally determined that when, at room temperature, approximately 60 torr of N_2 is combined with 6460 torr of ^{3}He, there is the highest possible collision rate without having an adverse consequence on experiments.

Ultimately, polarized ^{3}He is the goal. The Rb polarizes the ^{3}He through its collisions. A hyperfine interaction causes the spin of a nucleus to interact with the spin of the Rb electron. In this case, the polarized Rb electrons interact with the nucleus of the ^{3}He atoms in such a manner that the Rb electron exchanges its spin with the ^{3}He nucleus. Since the optical pumping continues to take place, the Rb electron is re-polarized after it changes its spin. A high density of Rb is needed to ensure that there will be a large number of collisions. In order to prevent the ^{3}He nuclei from depolarizing, it is necessary to avoid impurities and to prevent the ^{3}He nuclei from interacting with the sides of the target cell.

The filling of a ^{3}He target cell is a process that takes multiple days. First, the target cell is baked while under vacuum in an oven to 470 degrees Celsius for seven days. During this period, the Rb is distilled by a torch. After the baking process is completed, the Rb is chased into the pumping chamber of the cell with a torch. After the Rb has been chased, the target chamber is placed into a dewar in which liquid ^{4}He is flowed, which cools the chamber to approximately 4K so that the internal pressure of the cell will not be as high as the pressure outside of the cell (atmospheric pressure). Once the cell reaches the temperature of 4K, it is filled with the proper amount of high-purity N_2, after which it is

filled with the proper amount of high-purity ^{3}He. The ideal gas law is used to determine how much gas is flowing into the cell, since the temperature, pressure, and volume are measured during the fill process. After the cell has been filled, the torch is used to melt the glass between the target cell and the glass tube to which it is connected. Since the pressure inside the cell is lower than the pressure outside of it, the glass collapses, rather than expanding, so that the cell is sealed off without leaking any gas.

It takes approximately 24-48 hours to polarize the ^{3}He to its maximum polarization, depending on the quality of the cell. Cells that have low potential polarization take less time. Once the ^{3}He gas has been polarized to its maximum level, there are a number of effects that can reduce the polarization of the target material: ^{3}He-^{3}He collisions, depolarization from the electron beam used at Jefferson Lab, inhomogeneities in the magnetic field, collisions with impurities and collisions with the cell walls. The first two of these causes cannot be controlled, but it is possible to reduce the effects of the other issues. Using large Helmholtz coils, such as the ones in the William and Mary lab, reduce this possibility. The last two effects can be reduced by paying careful attention during the cell production and filling processes. Glass re-blowing and nitric acid cleansing treatments prevent cell wall impurities, and maintaining a clean cell-fill system prevents impurities from entering the cell during the filling process.

3. The Oven

There are very precise specifications for the oven. First, it has to be made of material that can sustain temperatures as high as 180 degrees Celsius. It also has to be non-magnetic and non-metallic so none of the oven parts will interact with the magnetic field created by the Helmholtz coils or the NMR RF field. There are also optical windows at its front and back, as an entry and an exit for the laser beam. These optical windows are three inches in diameter, and they are centered on the upper chamber of the target cell. The bottom of the oven has a hole in it that allows for putting cells into the oven. There is a second bottom plate that actually holds the cell in place, and it is attached to the first bottom plate with the use of teflon screws. The heating unit heats air that then flows into the oven in order to heat it. Temperature sensors and the heated air have access to the inside of the oven through the top plate. A schematic drawing of the oven can be found below in Figure IV, and the technical drawings that were used to build the oven can be found in Appendix A.

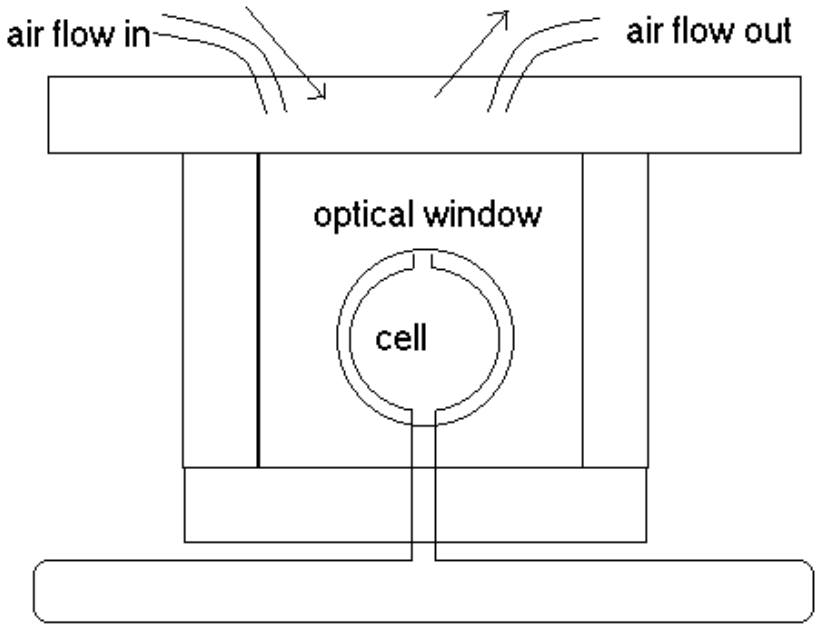

Figure IV: Schematic drawing of the front side view of the oven, which has an optical window through which the laser travels so that it can reach the upper chamber of the target cell.

We decided to use Teflon for the walls of the oven. Each of the side walls is 3/8 ” thick, while the top and bottom consist of plates that are ½” thick. The top and bottom plates are thicker in order to contribute to the structural integrity of the oven since they are the ones that have holes in them and that hold the cell in place. The overall interior dimensions of the oven are 3.25” by 3.25” with a height of 5.00”. The bottom consists of two plates: one that is permanently attached with a hole of 2.75” diameter in the middle so that the cell can be placed inside, and another plate that the cell is actually attached to. The second plate has a removable piece that holds the cell in place, and silicone is used to firmly keep it in place. The top plate is significantly larger than the rest of the plates; its dimensions are 8.00” by 8.00”. The top plate is larger so that there would be space for holes into

which rods can be inserted in order to attach the oven to the rest of the coil system. There will be holes in the top plate in which the heating unit and temperature sensors will go. The front and back plates are identical, each having a 3" lipped hole in which the optical windows are held in place by small pieces of plastic.

The other difficulty was in finding a way to suspend the oven within the system without distorting the magnetic field and without huge construction issues. It was determined that the best way to suspend the oven was to attach it to the poles that hold the RF coils in place. Another larger plate was created, of dimensions 16.875" by 23.75", which is attached to the poles. Four rods attach the top plate of the oven to this plate so that the oven can be suspended inside the system. There are also shields around the oven to block laser light from burning the protective curtain in the lab after being on for long periods off time, as well as to protect people both from reflected laser light and from glass in the instance of the cell breaking and exploding. These shields are made of red fiberglass. The color is necessary in order to prevent most of the light from penetrating the shields, and fiberglass was determined to be a usable material for the shields because it does not melt from the laser being directed at it for long periods of time.

4. The Oven Controller Unit

The oven controller is the mechanism that directs the heating unit of the oven to turn on or off, depending on the temperature inside the oven. It is a PID controller, which stands for proportional, integral, and derivative. These are the steps that the controller takes to

determine whether the heater should be turned on, off, or at what power level. The proportional term relates to how the controller reacts based on how far off-target the temperature is. The derivative term relates to how the controller reacts based on how quickly the temperature is changing. The integral term relates to how the controller reacts based on the sum of the error terms between the target temperature and the actual temperature. In order to calibrate the system, there is an automatic process that can be used. It is also possible to use a manual process to calibrate the system. In the system in the lab, the manual procedure and the automatic process results both worked with approximately the same success level to accurately control the heater after shocks to the system, such as lowering the target temperature. With both calibrations, there was a large overshoot when the target temperature was suddenly reduced. However, the oven controller responded very well to the external shock of the laser being turned on. The oven maintained the target temperature within 2 degrees when the laser was turned on. Thus, the oven controller needed to recognize the new source of heat and reduce the power to the heaters as the laser continues to provide more heat to the system, and it successfully did so.

The RTD, which is inside the oven, measures the temperature inside the oven. The RTD is a simple, yet accurate, device that uses resistance to determine temperature. The temperature reading is then sent to the controller. The controller turns the heater on and off through the relay. If the heater is off, but the temperature within the oven is not hot enough, then the controller sends a signal for the heater to turn on. If the heater is on, but the temperature within the oven has surpassed the necessary temperature, then the

controller sends a signal for the heater to turn off. A schematic drawing of the oven controller unit is illustrated in Figure V.

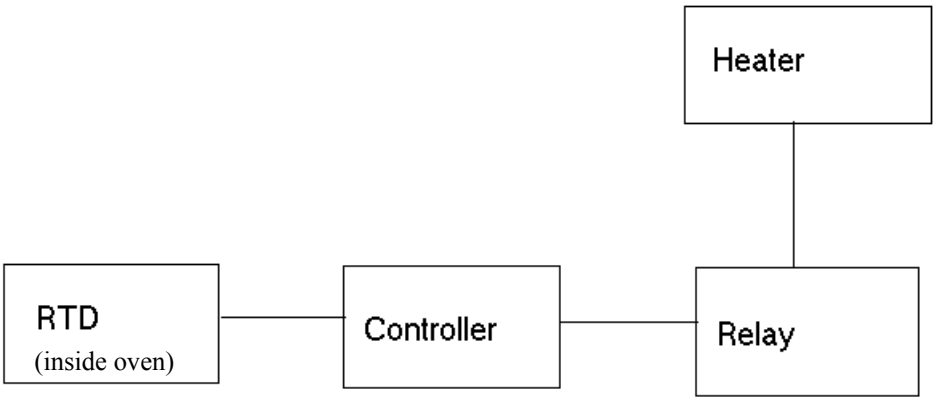

Figure V: The oven controller system. It shows the connections between the heaters and the temperature inside the oven.

5. Laser and Optics Setup

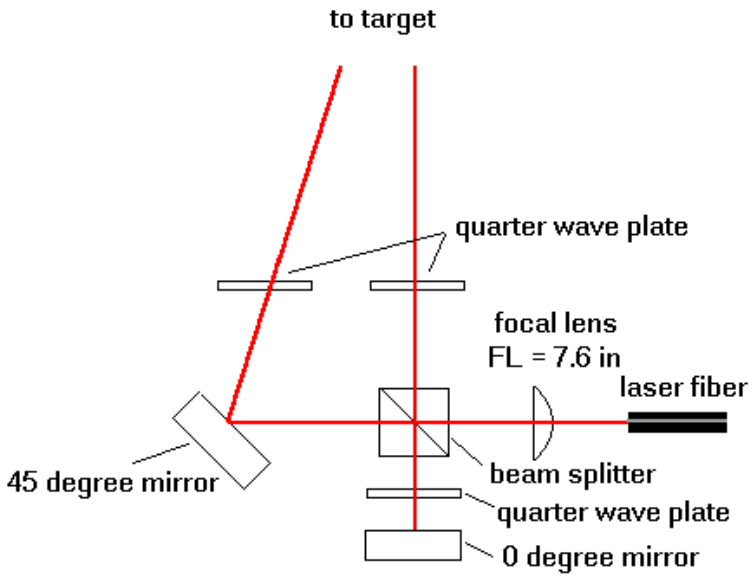

Figure VII: Schematic drawing of the laser and optics setup. The laser light travels through the polarizing beam splitter cube, and half of the light continues in the same direction and is reflected towards the target by a mirror, while the other half is reflected 90 degrees to the left, and is reflected back towards the target by another mirror.

Figure VII shows a schematic drawing of the laser and optics setup. The laser and optics setup is used to polarize the ^{3}He target cell. The laser is directed through a lens of focal length 7.6 cm, which acts to focus the laser beam. After the lens, the laser beam passes through a beam splitter cube, which splits the laser beam into two beams that are linearly polarized in orthogonal directions. One continues straight and hits a 45-degree mirror, after which it passes through a quarter wave plate before hitting the front optical window of the target cell. The other beam is reflected 90 degrees to the left, at which point it passes through a quarter wave plate, then hits a 0-degree mirror, reflects back through the quarter wave plate again, follows through the beam splitter cube, and passes through another quarter wave plate before hitting the front optical window of the target cell. Since one of the beams passes through a quarter wave plate two more times than the other, they are then polarized in the same direction. The quarter wave plates polarize the laser beam into circularly polarized light by slowing down one component of the electric field within the laser light and speeding up the other component of the electric field within the laser light so that they are out of phase by 90 degrees. This process happens because there are two axes in the plates, a fast axis and a slow axis. The effect that being out of phase has on the laser light is that it is circularly polarized because the net orientation of the electric field is no longer continually pointed along the same line, but instead changes direction so that it traces out a circle after a single cycle.

Before it is possible to use the diode laser in the optics setup, it is important to align the optics using a smaller laser, such as a laser pointer. The first step in this procedure is to

make sure that each piece of the optics setup is at the same height, including the laser. It is also necessary that this height is on the same level as the target. The first pieces to put into the setup are the mirrors and the polarization beam splitter cube. After checking that the laser beam is where it needs to be, it is possible to put the focus lens into the setup, between the laser and the polarizing beam splitter cube. To determine the optimal place for the focus lens, it is necessary to check the size and quality of the beam spot on both the polarizing beam splitter cube and the target. It may also be helpful to check the beam spot on the mirrors and the focus lens. It is now possible to put the quarter wave plates into the setup. Continually checking to make sure that the laser beam is where it should be is important. With regards to the quarter wave plates, they need to all be in the same direction, meaning that the fast and slow axes need to be in the same place on each of the plates. It is possible to tell where the axes are using a power meter and two polarizing beam splitter cubes. This method only distinguishes where the axes are, however, and not the fast axis from the slow axis. It is also possible to determine whether two quarter wave plates have the same or opposite orientation with the use of a power meter. Testing each of the quarter wave plates in pairs distinguishes whether they are all in the same orientation; if one of them is different from the other two, then that plate only needs to be rotated by 90 degrees so that they are all in the same orientation.

6. Polarization Measurement

A number of different methods are used to measure the polarization in ^{3}He target cells. The method used in this lab is the adiabatic fast passage method (AFP). This method

involves the application of an RF drive field of 91 kHz, perpendicular to the Helmholtz magnetic field. The strength of the Helmholtz magnetic field is varied from 25 G up to 32 G and then back to the original strength. During the ramping of the Helmholtz field, the resonance for ^{3}He is passed. When the Helmholtz passes the resonance, the nuclear spins of the ^{3}He atoms flip, reversing the polarization of the nuclei. The change in the nuclear spin directions causes a signal to be emitted in the pick-up coils; this signal is then amplified so it can be read. When the Helmholtz field is reduced, flipping the ^{3}He atomic spins back to their original polarization, another signal is emitted and read in a similar fashion. This process does not cause more than a minimal loss in polarization of the cell. This method is calibrated by following the same ramping procedure with a water-filled cell. In a magnetic field, water molecules have a small polarization that is easily calculated accurately. Since the height of the signal is correlated with the polarization of the contents of the cell, it is possible to determine the polarization of a ^{3}He cell through comparison to the signal from the water-filled cell. [7] There are a couple of limitations to this procedure, though. Identical cells are needed between the water cell and the ^{3}He cell in order to calibrate the system completely. It is also sometimes true that there are minimal variations in the resonance strength from day to day. [3] The Q-coil helps to determine these variations by measuring the frequency response of the pickup coils. A Q-coil test is run before each polarization test; thus it is possible to account for some of the variation in the sensitivity of the pickup coils.

7. Results

The goal of this project was reached over the course of the year. A target system was constructed including the coil system, the oven system, and the laser and optics system; a clear signal was read by the pickup coils, meaning that the ^{3}He gas was polarized. This signal can be seen in Figure VIII below. Since the coil system has not yet been calibrated using the water cell calibration method, it is not possible to know by how much the ^{3}He gas was polarized. However, both signals, from the ramp up and the ramp down of the magnetic field, were well defined. One interesting result is that the signal peaks were at slightly different magnetic fields; the spins flipped at a magnetic field of approximately one Gauss less during the ramp up than during the ramp down. This difference is due to a delay in the signal read by the pickup coils as compared to the signal sent to the Helmholtz coils; the spin flip is actually occurring at the same magnetic field strength each time. A cell was also filled this semester. While tests have not been run on this cell, the cell fill ran very smoothly.

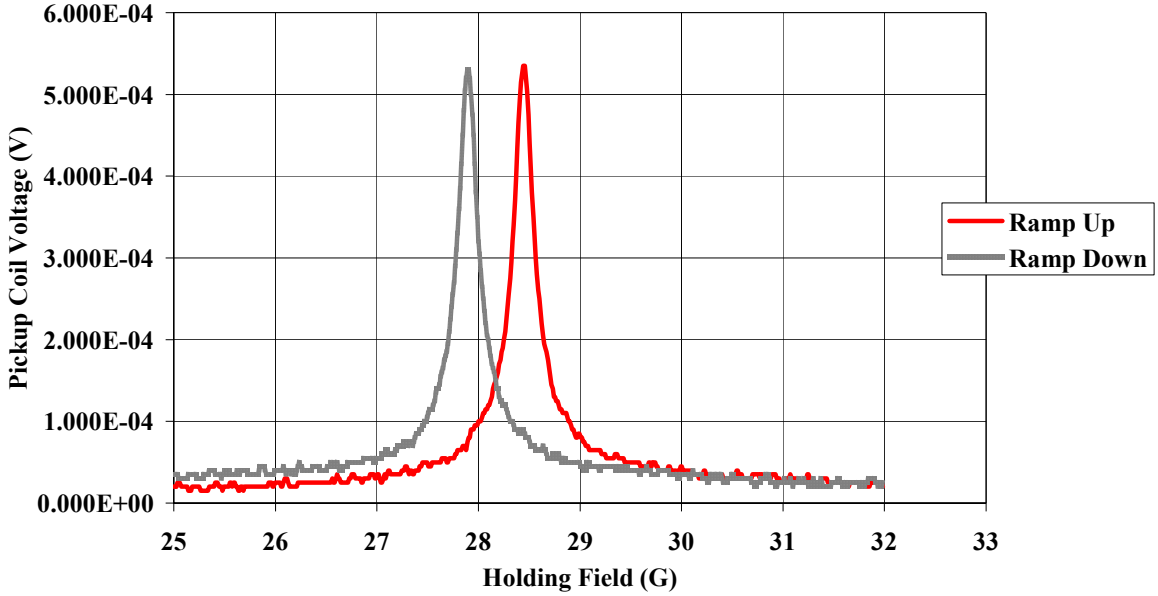

Figure VIII: Signal read by the pickup coils after the polarization.

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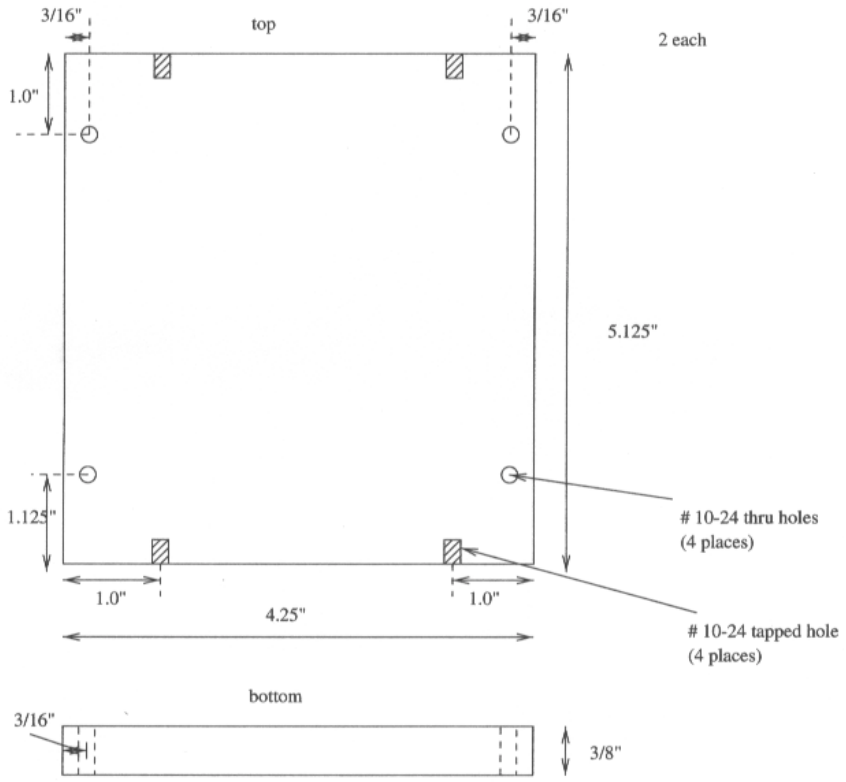
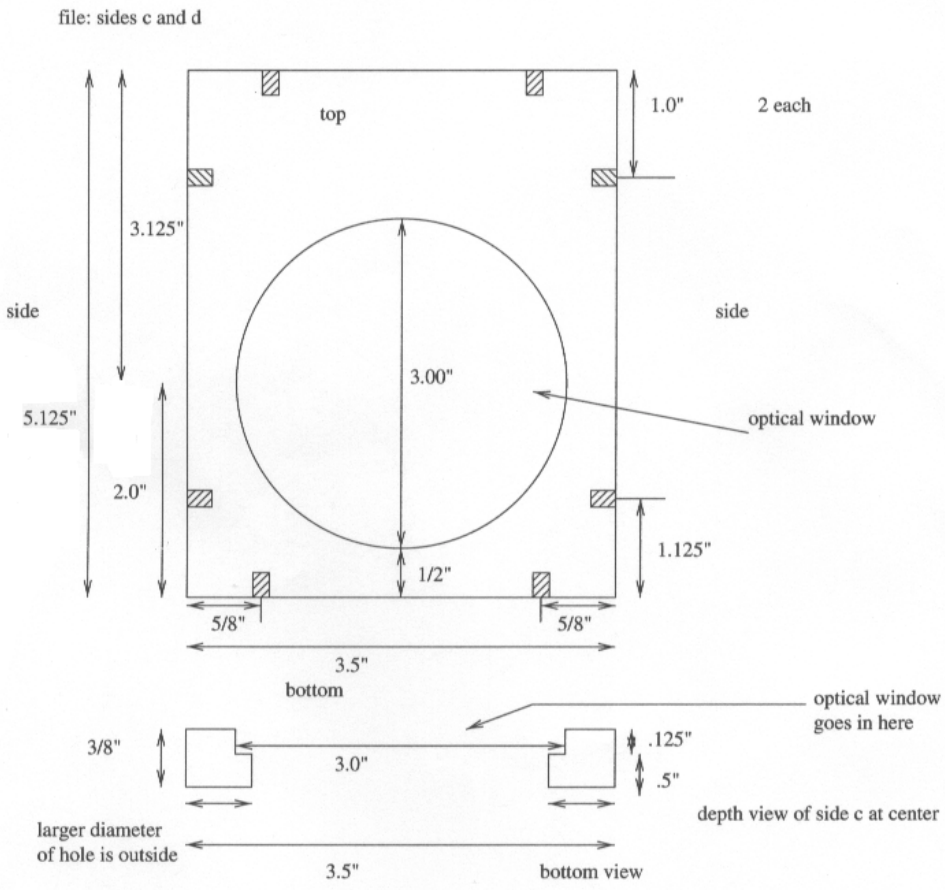
APPENDIX A: OVEN DRAWINGS

file: sides a and b

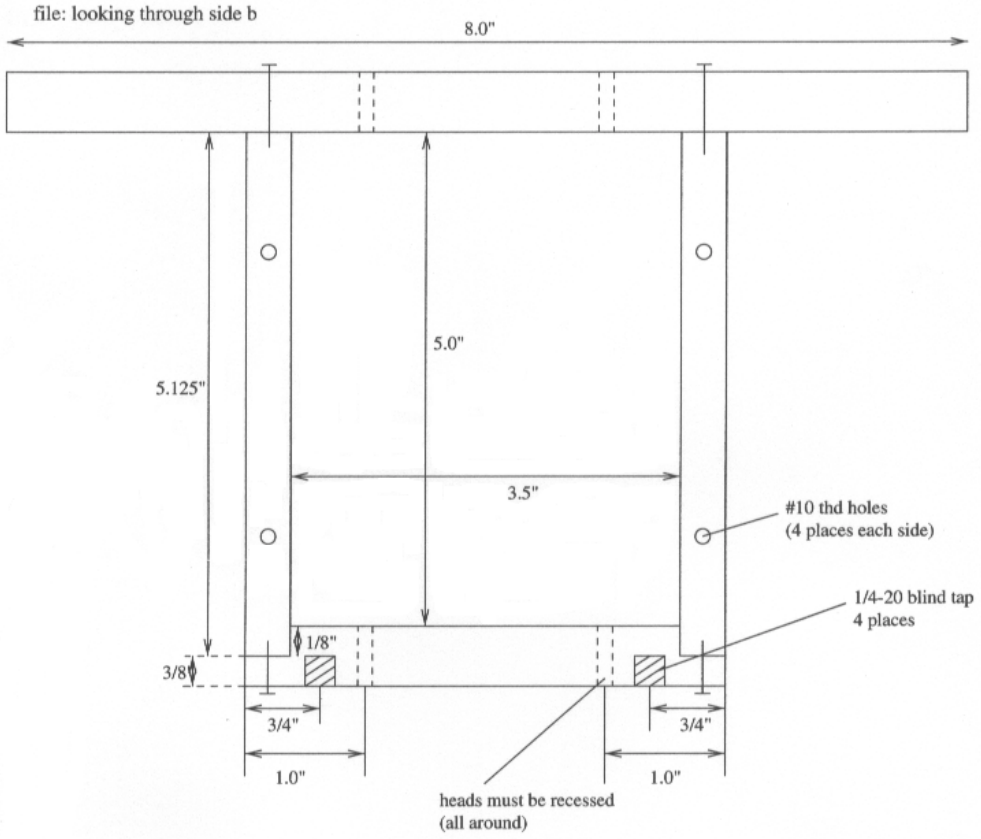


Drawing of the side plates of the oven.



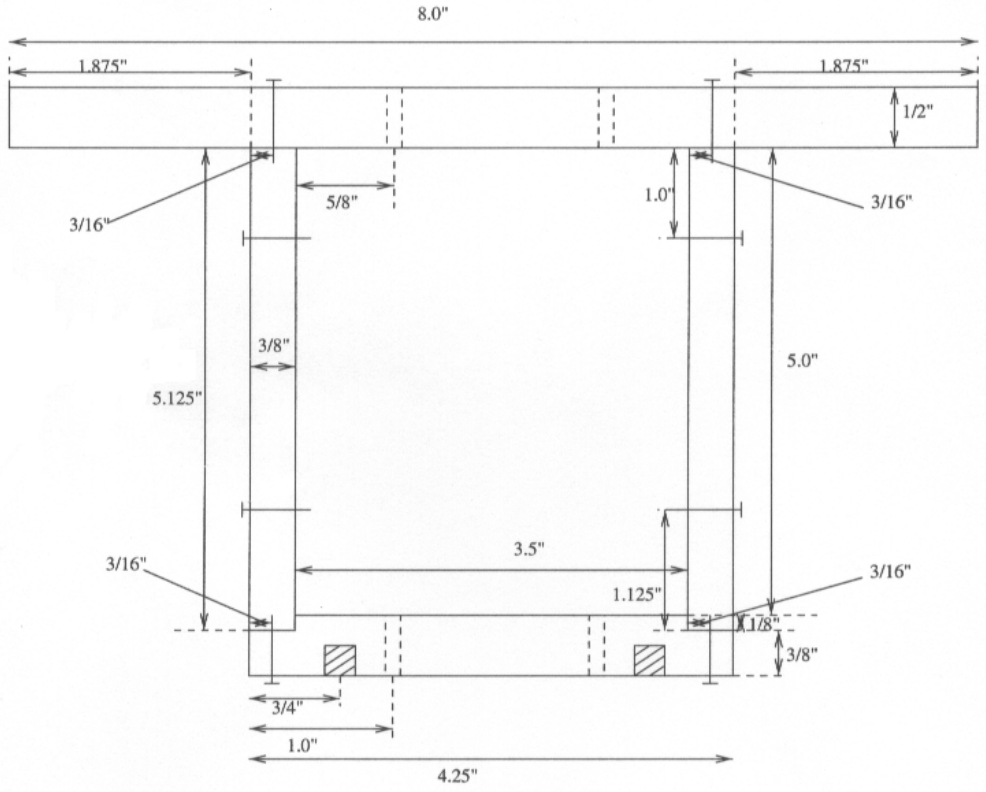
Top: Drawing of the front and back plates of the oven.

Bottom: Drawing of the profile of the plate at the center of the hole for the optical window.



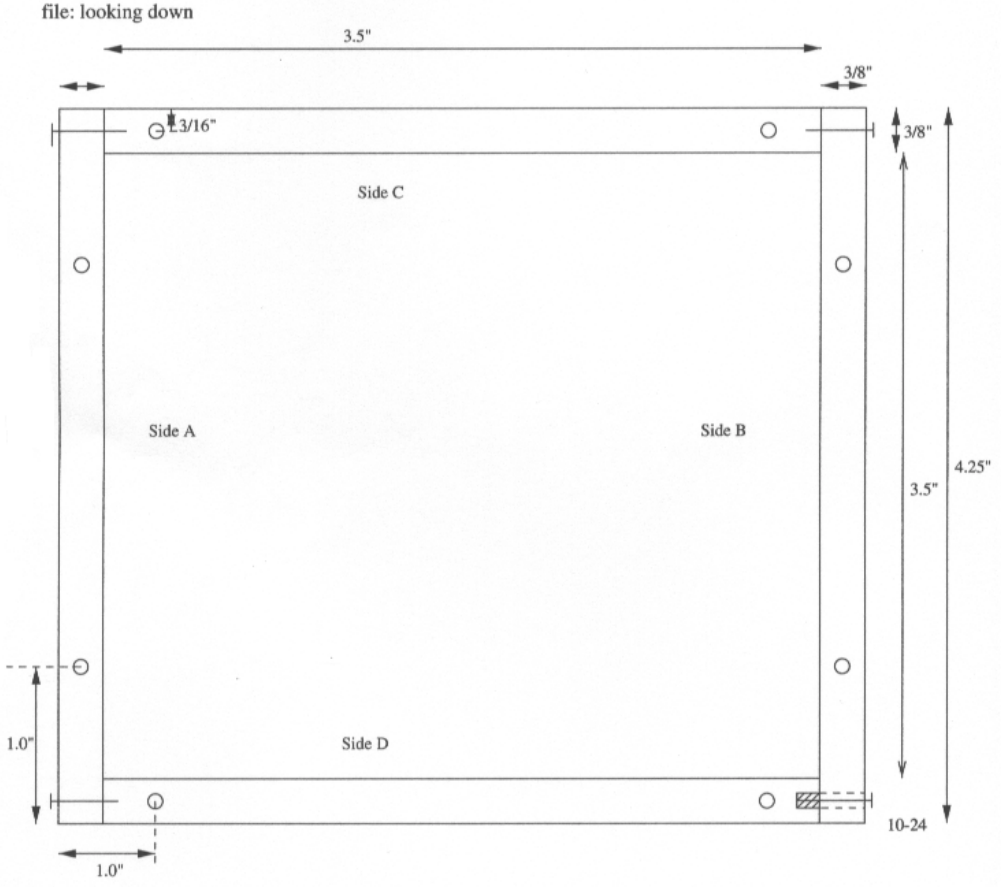
Drawing of the view through the side of the oven.

file: looking through side c



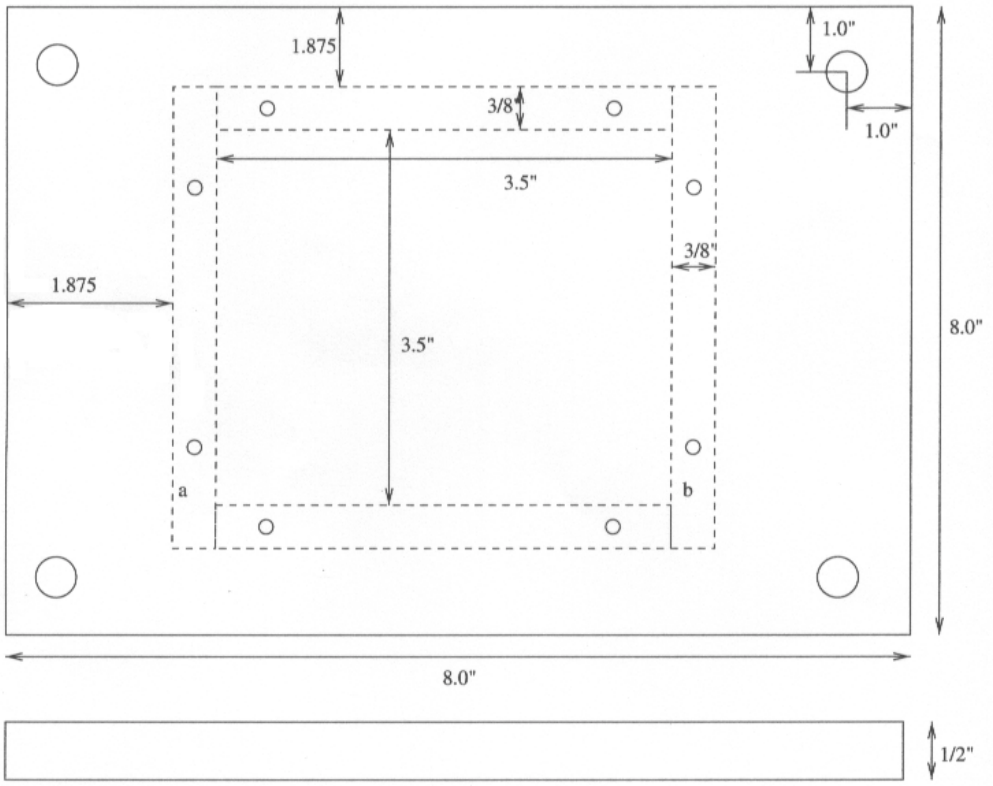
Drawing of the view through the front of the oven.

file: looking down



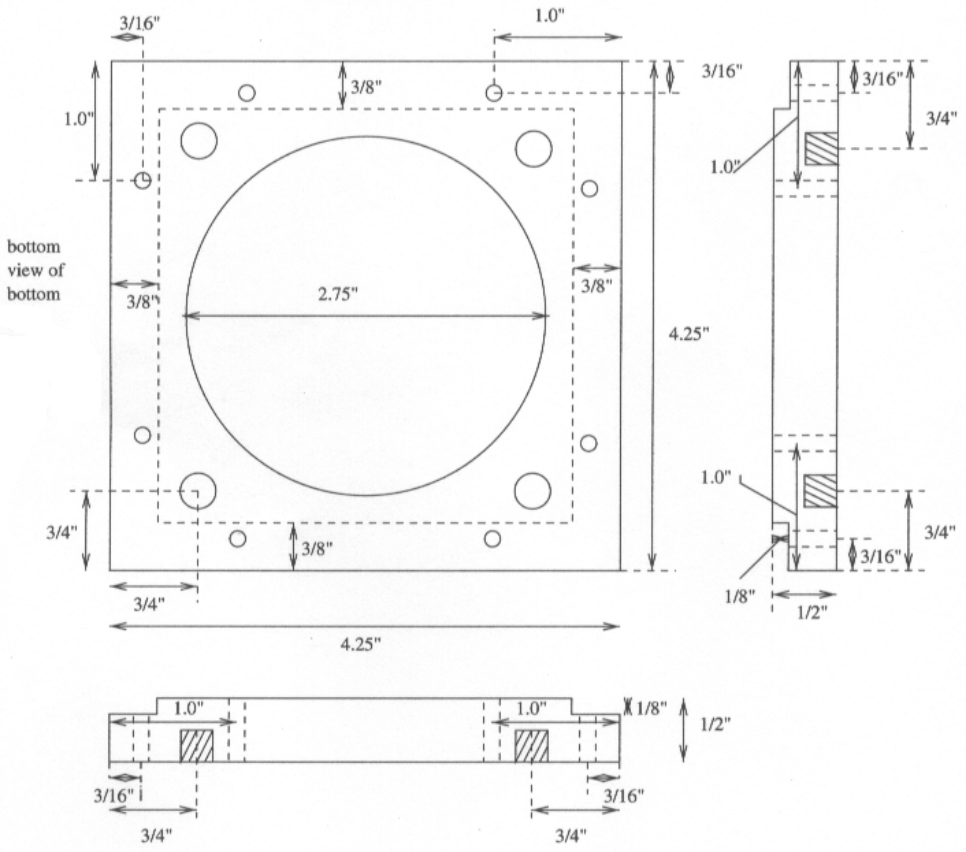
Drawing of the view through the top of the oven.

file: top

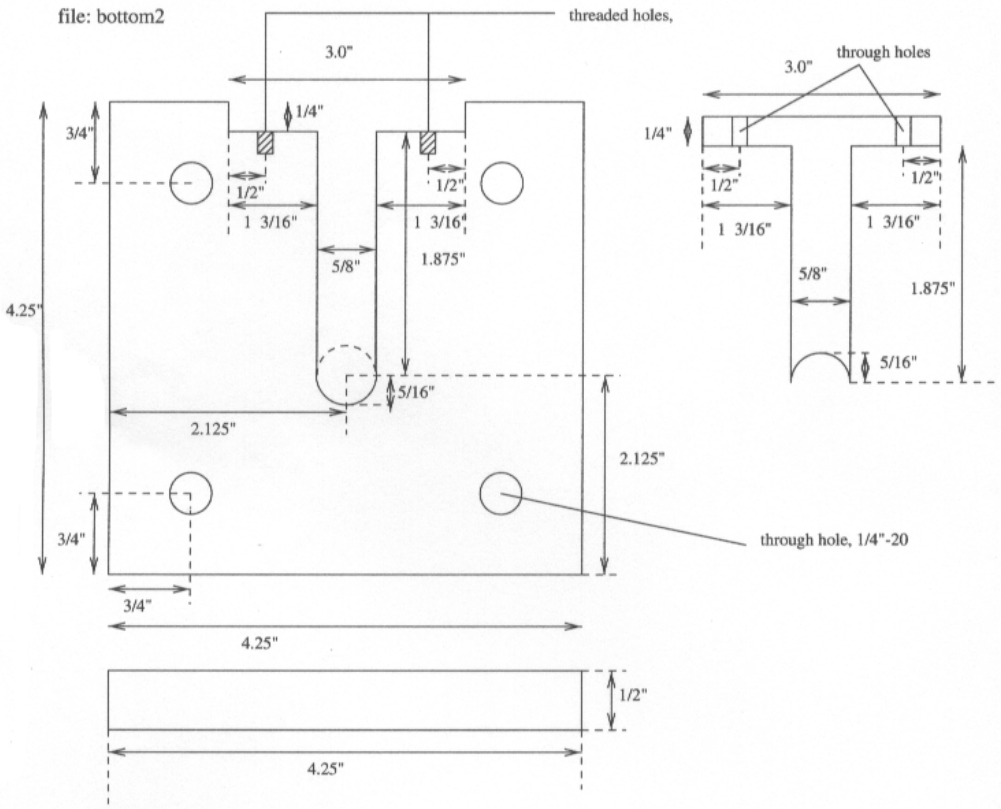


Drawing of the top plate of the oven

file: bottom



Drawing of the first bottom plate of the oven. The edges of the plate are not as deep so that they make a seal with the side plates.



Drawing of the second bottom plate of the oven. The piece on the right side is removable and screws into place after a cell has been slid in.