Equipment Designed for the Growth of CdZnTe Crystals by the Traveling Heater Method Under the Influences of Static and Rotating Magnetic Fields

By

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In the Department of Mechanical Engineering
We accept this report as conforming to the required standard

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ABSTRACT

CdZnTe semiconductor crystals are being used in a wide variety of gamma-ray detector applications as well as a substrate for HgCdTe infrared detectors. High pressure Bridgman is the most common method of growing single CdZnTe crystals though it typically produces crystals with inconsistent composition uniformity and high defect densities. Usable crystals must be mined out of material filled with grain boundaries and flaws. The Traveling Heater Method (THM) has the potential to grow single CdZnTe crystals with uniform composition and few defects. THM is not widely used due to its low growth rate leading to low productivity. The major limitation to the rate of THM crystal growth is the transport of the growth materials through the solution zone, which is facilitated by both diffusion and convection. Convection can be somewhat amplified by increasing thermal gradients. Diffusion rates however, are limited by the material properties. Large convection currents from thermal gradients have been associated with concave growth interfaces and unusable growth conditions that can lead to poor crystal quality or polycrystal development. Experiments growing crystals under microgravity to reduce convection while under the influence of a rotating magnetic field to generate controlled mixing have shown promise. This thesis outlines the design of an apparatus to grow CdZnTe in a 3mT rotating magnetic field (0 to 150 Hz). The apparatus allows for the later addition of a fixed 1.25T magnet to simulate microgravity conditions, as well as acoustic waves to aid in solution mixing.

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Table of Contents

Table of Contents

List of Figures

Glossary of Acronyms

CT	Computerized Topography
CZ	Czochralski
DRDO	Defense Research and Development Organization
FZ	Float Zone Growth
LPE	Liquid Phase Epitaxy
LPEE	Liquid Phase Electroepitaxy
MRI	Magnetic Resonance Imaging
NMI	Nuclear Medical Imaging
PDI	Proportional Integral Derivative
THM	Traveling Heater Method
VB	Vertical Bridgman
VGF	Vertical Gradient Freeze

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1 Background

1.1 Introduction

Over the last decade there has been an increased use of semiconductors in a variety of fields including microwave devices, low threshold injection lasers,[1] to optical switches, and gamma detectors for nuclear medical imaging. This has led to an increased demand for large high quality single crystals for a variety of applications. In the field of gamma ray detection Silicon and Germanium are the most widely used crystals. However, there are some limitations with these materials due to their low absorption and high thermal noise. At present one of the most promising crystals for the detection of gamma rays is Cadmium Zinc Telluride (CdZnTe). Much research is needed to find repeatable methods to grow large, high quality CdZnTe crystals. One of the most promising areas to focus that research is the Traveling Heater Method (THM).

This chapter will outline the different crystal growth techniques, give a review of the published work done on THM, and review some of the techniques that are being explored to improve THM such as growth under fixed and rotating magnetic fields. The chapter will also outline the use and production of CdZnTe and explain the objective of this thesis.

1.2 Crystal Growth Techniques

Below, various crystal growth techniques are briefly introduced. Their main features, advantages and disadvantages are given.

1.2.1 Vapor Growth Techniques

There are several different vapor growth techniques including seeded, unseeded and sublimation traveling heater. These methods typically produce high quality crystals with low point defects and dislocation densities. This is due to the low temperature gradients that the crystals experience during growth. The major disadvantages of vapor growth techniques are their low growth rate and high start-up and operating costs.

The typical apparatus for vapor growth can be seen in Figure 1. A growth chamber is repeatedly flushed with an inert gas and evacuated. Source material is held on a course silica mesh and under it a seed crystal is held on a sapphire rod. The approximate temperature profile is shown in the Figure 1.

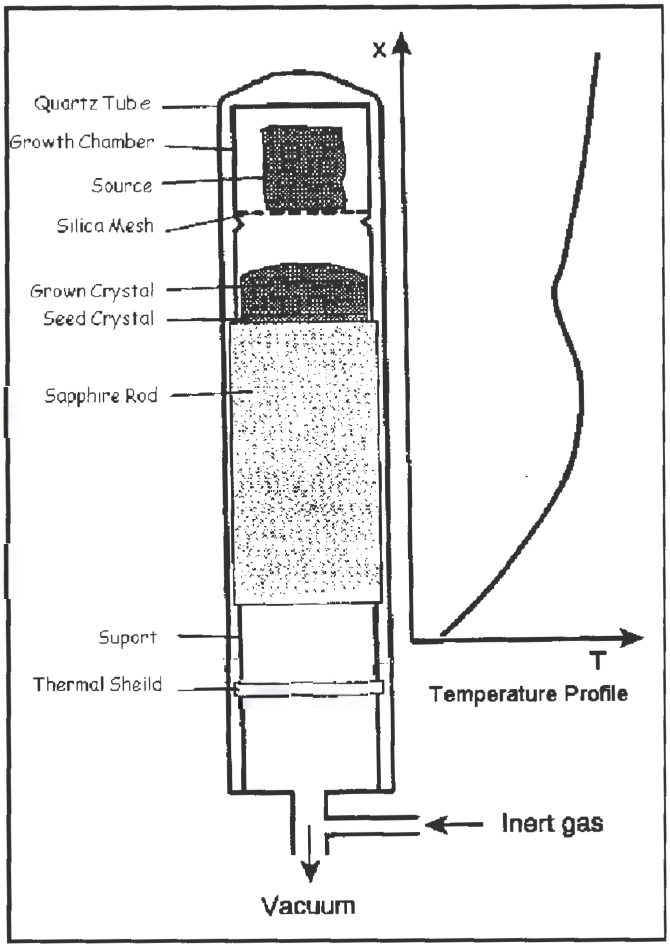

Figure 1 A typical Vapor Growth Setup

Due to its high cost, vapor growth techniques are reserved for the growth of crystals for very demanding applications where very high purity and low defect densities are required. Since the crystals are exposed to low thermal and no container stresses during growth, the quality that can be achieved by these methods are better than any other. Crystals have been grown in space by these techniques that have no faults.[2]

1.2.2 Growth from Liquid Phase (Melt)

In liquid phase crystal growth the crystal is grown by cooling a liquid of the same concentration as the grown crystal. The apparatus is generally less costly than vapor methods by the crystal can have concentration variations and other flows related to the high temperatures of these growth methods.

1.2.2.1 Bridgman

The Bridgman technique achieves growth from a melt. There are two widely used methods in Bridgman crystal growth; horizontal (HB), and vertical (VB). Each has its own advantages and disadvantages, however the basic mechanisms of growth are the same for both and will be discussed here. The crystals are grown in a furnace with three temperature zones; hot, insulated, and cold. An ampoule is loaded with a seed (can be unseeded) and charge material this is positioned inside the furnace such that the seed is only partially melted and the charge material is completely liquid. The ampoule is then moved relative to the temperature profile, this can be done by moving the ampoule in the direction shown in Figure 2 or moving the furnace in the opposite direction. New crystal material is grown on the seed as the ampoule is moved through the cooling temperature gradient.

The Bridgman method is one of the most widely used techniques to grow a variety of bulk crystals. It has the advantage of having the hot zone above or beside the cold zone, resulting in less convection currents in the melt. There are lower thermal stresses in the grown crystal than in the Czochralski method, but since the crystal is grown in an ampoule, container pressures from different rates of thermal expansion can cause stresses in the grown material. The use of an ampoule has other limitations. At higher temperatures the containers may leach small amounts of impurities such as Si and O_2 in to the melt, also ampoules are only available in sizes smaller than the maximum size of other growth methods like Czochralski. Since the Bridgman apparatus requires the use of some mechanism to move the furnace, or ampoule, vibrations can lower the quality of the grown crystal. Bridgman crystal growth has been used for a large number of crystal types. Its relative low cost and high yield make it very robust as a method for the growth of crystal of one element like Silicon as well as a large number of ternary alloys.

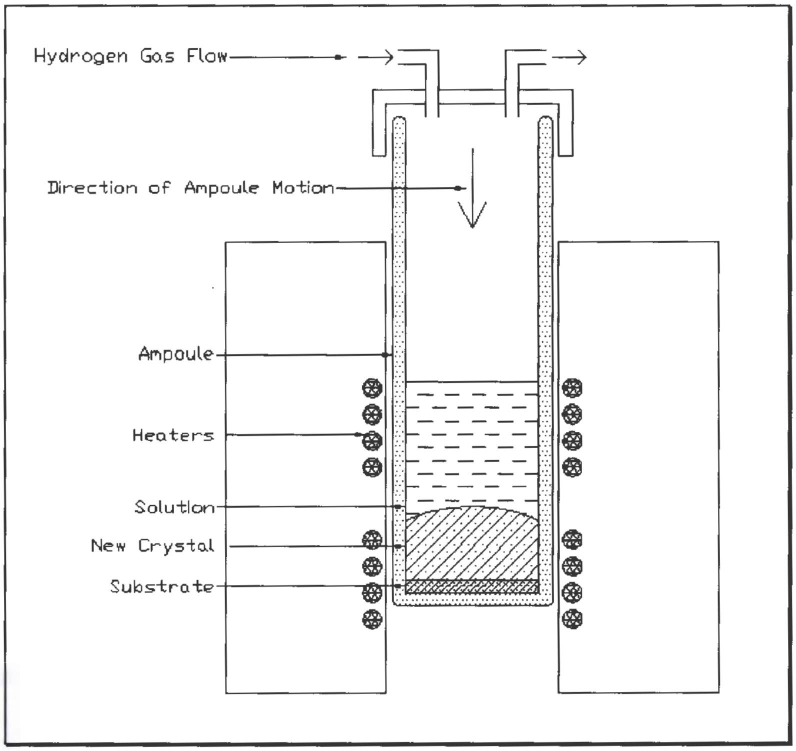

Figure 2 Vertical Brigman Method

1.2.2.2 Vertical Gradient Freezing (VGF)

The method of vertical gradient freezing (VGF) has many similarities to the Bridgman method. The ampoule is set up in a similar manner with seed and source material, however both the furnace and the ampoule are stationary. Instead, the temperature profile in the furnace is allowed to move upwards by cooling the heated zone. In some Bridgman apparatuses the furnace has multiple zones that are fired consecutively, resulting in a moving temperature profile. This setup is so similar to the VGF that there is some confusion as to whether there is any difference between the two methods. In either case the advantages, drawbacks and application of VGF are mostly the same as the

Bridgman. One exception is that due to no mechanical movement of the furnace or ampoule, VGF has none of the problems associated with mechanically moving parts.

1.2.2.3 Czochralski (CZ)

The basic apparatus for Czochralski (CZ) crystal growth can be seen in Figure 3. The charge material is heated above its melting temperature in a crucible. Then a seed is dipped into the melt and slowly withdrawn while being rotated. The entire apparatus is enclosed and ambient gasses are controlled. Power to the crucible and the rate of pull must be adjusted for the type and diameter of crystal grown. In some cases the grown crystal is cooled through the pull rod, or the entire crucible is encapsulated in an ampoule.

In the Czochralski method the grown crystal is not in contact with any mould. This means that the crystal can be grown in a variety of diameters, depending on the thermal profile and pulling rate used. Depending on seed orientation, a crystal can be grown in any orientation and with a variety of different dopants. In many pulling growth apparatus, the crystal growth can be observed in situ. This is a major advantage in optimizing growth parameters[3].

The main disadvantage of the Czochralski method is the adverse effect on crystal quality caused by temperature and concentration changes during growth. Since the coldest zone in the melt is at the top where the crystal is grown and the hottest at the bottom, opposite of the equilibrium state, very high convective flow develop in the melt. This convection leads to varying growth rates from changing temperatures and consentrations in the melt. When growing crystals of more than one element or from impure material these changes lead to nonuniform crystal properties and concentration striations.

The Czochralski method is widely used for the growth of silicon, sapphire and GaAs. Silicon is well suited for growth by CZ because of its high thermal conductivity and critical resolved shear stress.[4] This means that it can be pulled quickly from the melt and the thermal stresses in the crystal are less likely to generate dislocations

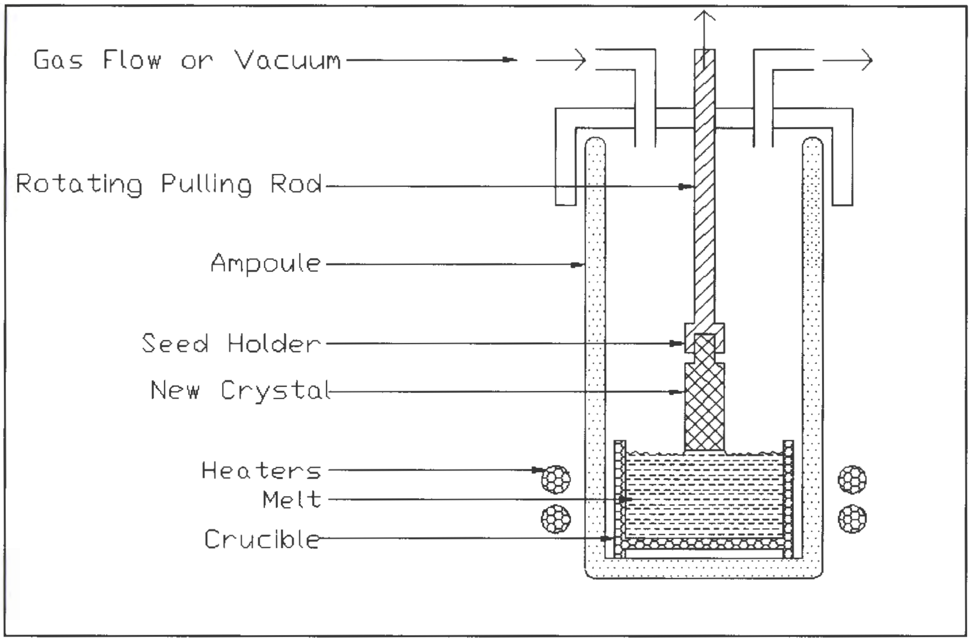

Figure 3 A Typical Apparatus Used for Czochalski Growth

1.2.2.4 Float Zone (FZ)

Crystal growth by the float zone technique is achieved without the use of an ampoule or crucible in contact with the crystal or growth material (Figure 4). A cylindrical charge is placed on top of a seed and heated by radiation at the seed charge interface by a torus shaped heater. The molten material is held in place by surface tension. By moving the heater up, source material is melted while liquid material is cooled and deposited on the crystal. Most crystals require an inert gas environment to avoid contamination. In some applications surface tension is inadequate and a platinum ampoule is used.

Like Czochralski growth the major advantage to float zone growth is that in most cases it does not require a growth ampoule or crucible. This eliminates container stresses from differences in thermal expansion as the crystal cools, and also the possibility of contamination from the crucible. However, like in Czochralski growth, there are very high thermal gradients during FZ growth that can lead to striations. Float zone technique is often used for Silicon and Germanium crystals. The method does not work for growth of ternary crystal as uneven dopants can be deposited in layers; also material that decompose at their melting point do not work well with this method.

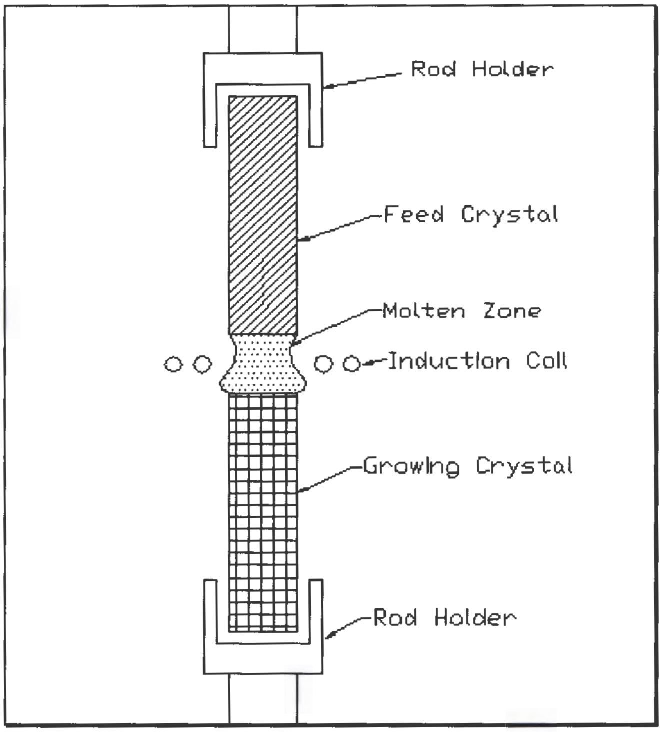

Figure 4 Apparatus used for Floating Zone Growth

1.2.3 Solution Growth

All solution growth techniques have some similarities. Since the growth material is in solution and not in molten form operating temperatures are lower. This can eliminate or reduce many problems such as vapor pressures and high convection currents in the liquid solution. In addition, grown crystals generally have less thermal stress. The common disadvantage of solution techniques is their low growth rate that is caused from the slow diffusion in the growth liquid solution.

1.2.3.1 Traveling Heater Method (THM)

Like all solution growth methods THM induces crystal growth by supersaturating a solution of the growth material. In the case of THM, lowering the temperature of the solution on the interface between the seed crystal (in the case of seeded growth) and the solution create this supersaturation. As this growth interface progresses forward so does the temperature profile, continually maintaining a lower temperature at the crystal solution interface than the rest of the liquid solution. Coinciding with this moving temperature gradient that advances with the growth interface, is another temperature gradient that increases the temperature at the liquid-source interface (dissolution interface), continually dissolving more source material and maintaining a constant solute concentration in the liquid solution. See Figure 5. This ability to maintain a stable solute concentration during growth is a major advantage of the THM growth method.

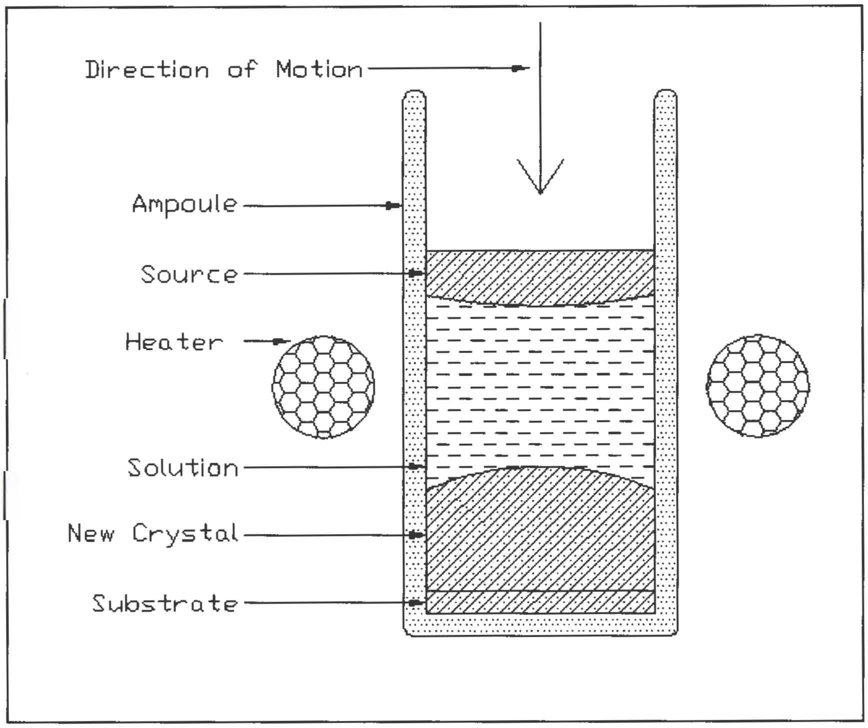

Figure 5 THM Growth Apparatus

In order to achieve the growing conditions described in the above section, an axial temperature profile with a spike or bulge must be created. The most important part of the temperature profile spike is the gradient of the leading slope. It is this gradient that causes the supersaturation in the solution resulting in crystal growth, therefore it plays an important role in the growth rate, along with concentrations in the vicinity of growth interface. This gradient can also cause and increase the magnitude of buoyancy driven convection currents. These currents can lead to a concave shape of the growth interface,[5] a situation that can trap impurities and dopents in the crystal lattice leading to flaws or polycrystalline materials. In the case of seeded growth, the precise position of this gradient with respect to the growth seed is essential but difficult to obtain in experiments. The gradient in THM is achieved by heating an area of the growth furnace while cooling another just below it.

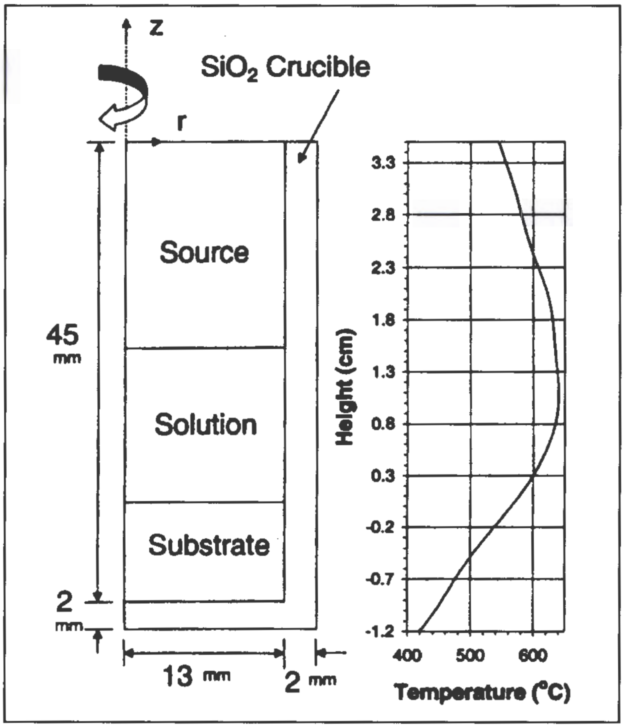

Figure 6 THM Ampoule and Temperature Profile (Meric et. al. 1999)

The typical temperature profile used for THM growth can be seen in Figure 6. A furnace holds an ampoule mounted either horizontally or vertically, with one torus shaped heating element positioned around it. On the growth side of the heaters the furnace is cooled by conduction and typically has little or no insulation. In some cases direct contact is made between the ampoule and some cooling fluid or a high conductivity metal bar, rod or plate that is cooled by some other medium.[6] The ampoule is mechanically moved at a constant rate between 1 and 4 mm per day through the furnace until all of the feed material has been melted and deposited as new crystal. A variation of this setup is one where the temperature profile of the furnace can be changed. Closely positioned independently fired resistance heaters are positioned around an ampoule. The heaters are consecutively fired in such a way as to move a temperature spike forward while the ampoule remains still. This system has the advantage of having no mechanical moving parts, which makes it vibration-free. Vibration has the potential to disturb the growth and lower crystal quality.

1.2.3.2 Liquid Phase Epitaxy (LPE)

Like all solution growth techniques, LPE crystal growth is driven by super saturation of a solution near the growth interface. There are two setups used for LPE growth; horizontal, and vertical. In vertical growth, an ampoule is loaded with seed, source, and solution material and placed in a furnace with a temperature gradient (hotter on top than on the bottom). The furnace is rotated so there is no contact between seed and solvent until the solution becomes saturated by dissolving the source material. Once the system has reach equilibrium at growth temperature, the furnace is rotated so that the substrate is on the bottom. The temperature is slowly lowered and the solution then becomes saturated, depositing material on the substrate (seed).

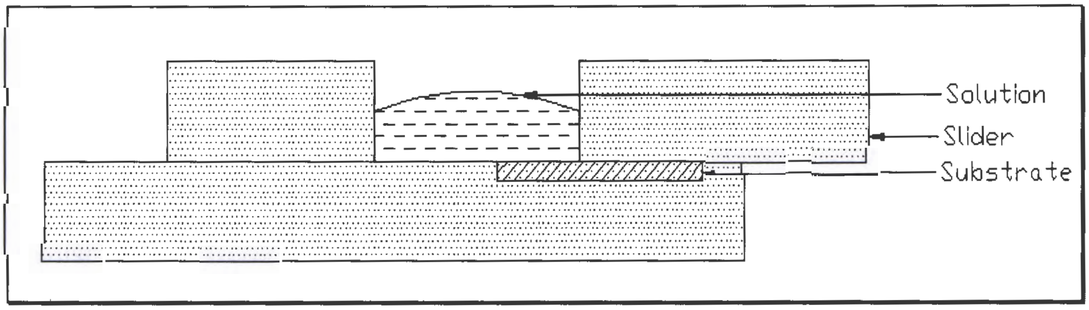

Figure 7 Simple Diagram of Sliding Boat Horizontal LPE Apparatus

Horizontal LPE uses a "sliding boat" crucible can be seen in Figure 7. This apparatus allows the liquid solution to be ramped up to the growth temperature while having no contact with the seed. Once the growth temperature has been reached the slider is moved over the seed and the temperature dropped gradually to induce precipitation on the seed. In some systems multiple sliders make it possible to grow several layers consecutively.

Apart from the basic advantages that are common to all solution growth techniques LPE is also one of the most inexpensive methods to start-up and operate. There is no moving of the ampoule, eliminating a possible cause of vibration and additional apparatus components. The furnace used is simple to manufacture and requires a reasonably simple controller. There is a limit to the size of crystal that can be grown by LPE, since once all the material in the solution is depleted, the growth stops. This feature along with the slow rate of growth common to all solution techniques restricts the use of LPE to specialized applications. An exception to this is the innovative "yo-yo" method of LPE growth, introduced by researchers in Shizuoka University, Japan; it allows the growth of crystals 20 times thicker than classical LPE[7,8,9]. Due to the significance of this technique, a large numerical of simulation models have been developed[10,11].

There are some instances where consecutive layers of crystal with varying composition and properties are required. Examples include transistors and crystals used for laser generation. Horizontal LPE is commonly used to deposit consecutive layers of doped, undoped or highly doped materials on a seed. The flat growth interface and uniform properties of materials grown by this method make it feasible, and since these layers are typically very thin the low growth rate does not constitute a disadvantage.

1.2.3.3 Liquid Phase Electroepitaxy (LPEE)

The set up of LPEE growth is similar to THM in many respects, however the driving mechanisms are different. Like THM, the LPEE crucible is set up with a seed and source with solution in-between, there is a continual growth on the seed and the source is slowly dissolved in the solution (Figure 8). This keeps the concentration in the solution close to constant. LPEE does not use temperature gradients to induce supersaturation and initiate growth, instead the entire crucible is held at a constant temperature and a direct electric current is passed through the solution and seed. This current induces crystal growth by three methods 1) dissolving the source due to localized Peltier heating, 2) transport by electromigration due to the electrostatic field 3) supersaturating the solution at the growth interface by Peltier cooling.

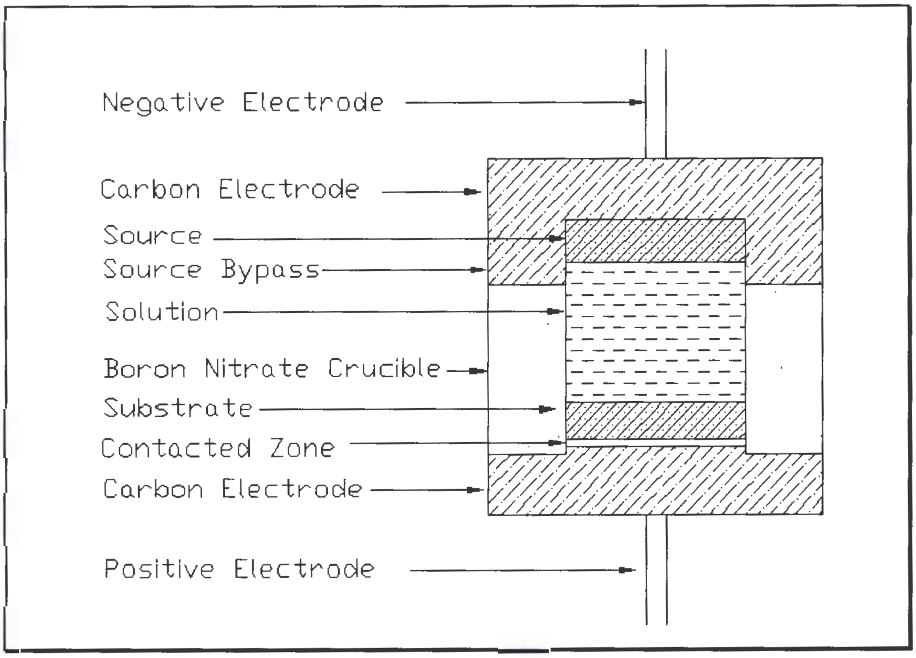

Figure 8 A Typical LPEE Crucible Setup

The advantage of LPEE growth is the high quality of the crystal grown, typically having both high purity and very low thermal stresses and dislocations. The growth apparatus is simpler and cost less than most vapor growth techniques, and growth rates can be faster.

Thus far, in the literature, the major disadvantage of LPEE was considered to be the small size of the growth layers. Growth of between 3 and 5 mm was thought to be the maximum possible as the Joule heating in the grown crystal starts to create problems with thermal gradients as the crystal get thicker. However, a state-of-the-art LPEE facility developed at the University of Victoria (Crystal Growth Laboratory) has recently led to the growth of very thick (up to 10 mm) ternary crystals. Researchers have been able to increase LPEE growth rates more than 10 times, with the combined effect of unique crucible designs and the use of external magnetic fields. Such developments in LPEE growth are making it a "bulk" growth technique.

1.3 Solution Concentration

As stated previously saturating the solution near the growth interface induces crystal growth in THM. The solute concentration in the small region near this interface is of great importance since it plays a major role in the rate of growth and the quality of the crystal grown. Figure 9 presents the variations of the solute concentration (C_L), temperature (T_{ACT}) and saturation temperature (T_{EQ}) at and near the growth interface. The solute concentration here could represent any element present in the solution including dopents and impurities.

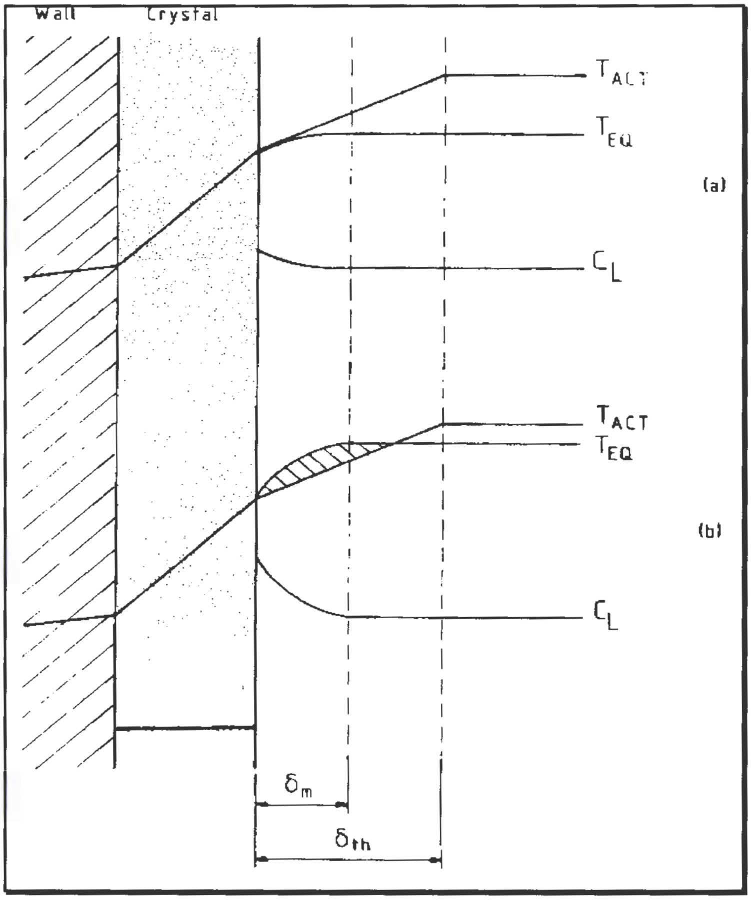

Figure 9 Concentrations under stable (a) and unstable (b) growth conditions (Hurle 1994)

Differences in solubility and the concentration in the crystal can cause some components to be at higher concentrations near the growth interface. It is not desirable to have high impurity concentrations in this region. However, without a forced mixing, the only mechanism to disperse the impurity is diffusion which is typically very slow in liquid metals. In order to have a practical growth rate (higher than 1 mm per day) the ampoule must move at a speed that will result in some concentration gradients. The saturation temperature is a value at which any temperature above will result in a undersaturated (and anything below an supersaturated) solution. During most crystal growth, there is some supersaturation in the vicinity of the growth interface. However, an excessive amount of solute will lead to rapid uncontrolled growth that could result in solvent inclusions and the development of polycrystalline material. The small hatched region in Figure 9b represents the degree of supersaturating and it should be kept to a reasonable amount. Keeping a steep temperature gradient in the solution can help to do this, as well as promoting forced mixing to reduce the concentration levels near the growth interface. Alternatively, a slower growth rate can be used; however, economically faster growth rates are better.

1.4 Contamination Considerations

High quality crystals must have high levels of purity. Since most crystal growth materials will oxidize at elevated temperatures an oxygen free growth environment must be provided. A vacuum is commonly used for this purpose. The ampoule is sealed at low temperature and a vacuum is applied through a valve at the top, limiting the amount of available oxygen in the ampoule. In cases where higher purity is needed hydrogen or some other reducing gas environment is used as a chaser. The ampoule is flushed through with hydrogen and then a vacuum is applied to remove any water or other impurities. Often this step is repeated several times. The use of hydrogen has some safety issues associated with it and, therefore, safety precautions should be taken. These include all necessary sensors and alarms.

1.5 Control of Growth Conditions

Similar to many fields, crystal growth has been under an ongoing pressure to increase the quality of its products. One of the methods that crystal manufactures and researchers have been investigating to control the growth conditions that influence the grown crystals is the use of magnetic fields. The application of external magnetic field influences the growth conditions in two ways. First, it suppresses the buoyancy driven convection in the solution that can lead to an unstable growth interface. Such conditions can cause solvent inclusion, nonuniform material concentration or polycrystalline growth. Secondly, the application of magnetic field gives rise to controlled mixing in the solution. Controlled mixing can reduce concentration gradients within the growth cell that can lead to unstable convection currents. It distributes solutes uniformly throughout the solution, making them available for growth. This helps to increase the rate of growth, and leads to a grown crystal with more uniform compositions.

One drawback of THM crystal growth is its low growth rate. This is due to the slow rate of solute diffusion in the solution. Suppressing the convection by means of applied magnetic field would further reduce transport in the solution and slow down the growth rate. However, high convection currents have been attributed to the development of a concave growth interface, which inevitably leads to a lower crystal quality. In an idealized situation there would be a slow but controlled mixing in the growth cell, whether by natural convection or induced by a magnetic field. Such controlled mixing would not induce a concave growth interface, but would eliminate temperature and concentration fluctuation at the interface. In turn, a stable growth concentration would minimize growth striations and non-uniform dopant concentrations. The mixing would also help increase the maximum growth speed. In order to achieve such ideal growth conditions, a complete understanding of convective flows induced from gravity, fixed and rotating magnetic fields is needed. Once this knowledge is gained, a combination of both rotating and fixed magnetic fields controlling the buoyancy driven convection may be able to help in achieving the aforementioned growth conditions[12].

1.6 Rotating and Static Magnetic Fields in Crystal Growth

Many researchers have used magnetic fields in both the axial and transverse directions to dampen convection flows and turbulence. A good body of research is focused on the Czochralski growth since the crucible used in this method is subject to high temperature gradients and therefore strong convection currents. These currents are responsible for uncontrolled temperature fluctuations at the crystal growth interface that cause nonuniform striations in the grown crystal.[13] It has been shown that a magnetic field of 0.1 T can reduce the temperature fluctuations at the growth interface from 9 to 0.3 ^{0}C and make marked reductions in resistivity fluctuations in some semiconductor crystals grown by the Czochralski method. However, axial magnetic fields have been seen to degrade the radial symmetry in the grown crystal and transverse fields can destroy the thermal symmetry and introduce rotational striations, in Czochralski growth. From the research done with fixed magnetic fields in Czochralski growth it is clear that they have the ability to dampen currents in the melt, however their negative effects on concentration uniformity due to reduced mixing is also considerable.

Most work done on other growth methods is numerical. Dost and Sheibani[14] preformed a numerical simulation of the LPEE growth of GaInAs with and without magnetic field (up to a 2 tesla field). The results showed a decrease in convection current velocities of 1000 orders of magnitude. This leads to a much more stable growth interface that was close to flat. Studies without magnetic fields showed two humps on the growth interface due to faster growth from higher concentrations caused by convection currents. This work not only shows that convection currents can be suppressed by a magnetic field but also that these currents have both good and bad effects. The currents can increase growth rate by increasing transport in the solution, but if this increase is not even over the entire crystal an uneven and unstable growth interfaces can result, leading to solvent inclusion and uneven concentrations in the grown crystal.

Mobner and Gerrbeth[15] did a numerical simulation of melt growth under both fixed and rotating magnetic fields. They found that a great variety of controllable flow structures were possible from any thermogravitational conditions, with the right strength and frequency of magnetic fields. This suggests a great opportunity for optimal crystal growth under the influence of both fixed and rotating magnetic fields.

1.7 Numerical Modeling

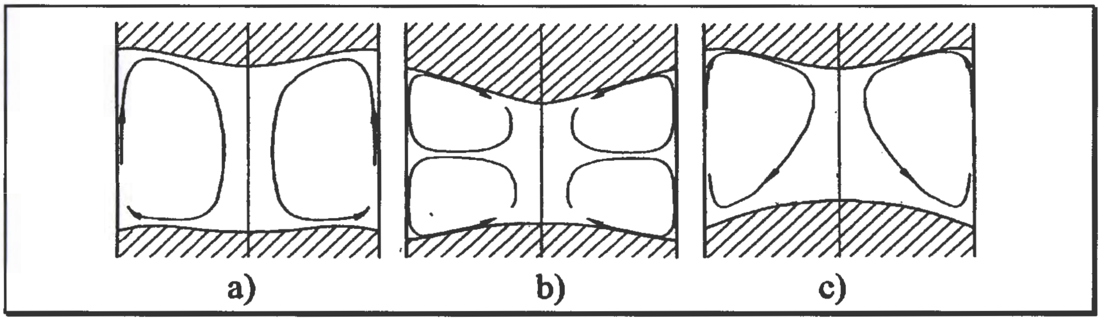

Figure 10 Connective Cells in Growth Solution under a) gravity and zero field b) zero gravity and zero field c) gravity and a RMF (Senchenkov 1998)

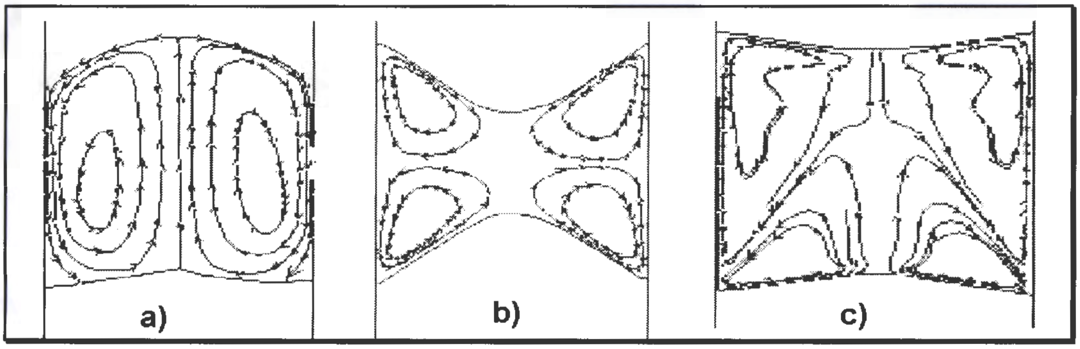

Figure 11 Connective Cells in Growth Solution under a) gravity and zero field b) gravity and a RMF c) zero gravity and a RMF (Microgravity News 1997[16])

Much numerical research has been done to try and find the effect of growing crystal from solution under the influence of a rotating magnetic field. Most of the numerical studies done show that rotating magnetic fields can induce or control mixing currents in liquid solutions.[17,18,19] This in turn leads to a stable and controlled solution-growth interface, better crystal homogeneity, and a faster growth rate. Numerical results are further supported by growth experiments done on both liquid phase and solution growth techniques. There is some uncertainty as to how strong a magnetic field is needed and at what rate it should rotate. These parameters could change depending on ampoule size and material being grown. Generally magnetic fields strengths between 2 mT and 15 mT and rotations between 50 and 400 Hz have been considered for rotating fields and between 0.5T to 5 T for steady magnetic fields. An experimental study done with CdHgTe by Senchenkov et al.[20] with a 2 mT magnetic field rotating at 400Hz grow crystals with much lower standard deviation of mole fraction than crystals grown without the RMF. There is not complete agreement between the results of all of the published work. The results of two different numerical models of the solution cells in THM are shown in Figure 10 and 11.

1.8 Literature Review

Researchers at the Chalk River Nuclear Laboratories in Canada used both the LPE and THM to grow CdTe for nuclear detectors. In their study published in 1977[21] they found that temperature gradient and growth velocity had the greatest effect, but were not the only parameters that influenced the number and size of Te inclusions in their crystals. Their experiments concluded that both LPE and THM could be used to grow inoculation free crystals if growth speeds where kept between 2-3 mm/h and temperature gradients above 5°C /mm. Their work fails to address other crystal quality concerns such as composition homogeneity and grain size.

Benz and Muller grew both GaSb and InSb by THM in the vertical and horizontal position.[22] Their work focused on the effect of different solution lengths. By varying the amount of solvent put in the charge the length on the solution would change; this in turn changes the radius of the growth interface. They found an optimum radius of between 7 and 10 mm in their 10 mm diameter samples. This was obtained by fixing the temperature profile and varying the solution length between 5 and 8 mm. Growth rates in the experiments were varied between 0.7 and 5.0 mm/day, with 2.5 mm/day being the fastest rates to yield inclusion free single crystal.

Similar work was done by Bischopink and Benz with InGaP and published in 1989[23]. Their experimental design made use of a 300W halogen lamp focussed on a 15 mm diameter ampoule. The apparatus successfully grew InGaP crystals between 0.8 and 1.44 mm/day. The length of the crystals grown is not given, but all of the analysis was done with the first 2 mm of growth suggesting only thin layer where achieved.

Bischopink and Benz published another work in 1991 with AlGaSb[24]. They used a similar furnace to the one in their 1989 work and grew crystals up to 17 mm long. Their longest single crystal was 112 mm long. Growth rates varied between 1.0 and 1.44 mm/day.

Bukert, Gille and Kiessling published a paper in 1991 that focussed on feed material preparation for THM runes with HgCdTe. They used Bridgman growth followed by VGF to remove any Te inclusions. Both of these growth procedures were performed in the same quartz ampoule without allowing the crystal to completely cool. The crystal was then cooled and removed from the ampoule, etched and used as feed material in a THM run moving at 1 mm/day. Their 16 mm diameter crystals showed good composition uniformity with standard deviations in mole fraction varying by as little as .003 in the axial direction and .005 in the radial.

There are only three known furnaces capable of growing crystals under the influence of a rotating magnetic field. All three were designed at the Splav Technical Center in Moscow Russia.[25] ZONA 4 is the oldest and is capable of growing crystals between 400-1300 ^{o}C with feed rates between 0.15-15 mm/h, makings it suitable for zone melting and THM. This furnace has a mass of 50 kg and maximum power output of 200W, it is capable of growing between 4-6 crystals and has been on several unmanned space missions to grow crystals in micro gravity. Some of the experiments that have been run will be discussed later. ZONA 8 is a much larger furnace with a mass of 100 kg and a maximum power of 1400W[26]. It is capable of growing up to 10 crystals under a rotating magnetic field. This author has been unable to find any published reports of its use. This may be due to economic pressure on the Splav Technical Center in Russian since the furnaces scheduled completion date of 1996. SKAT-AG is still larger, with a mass of 250 kg and a max power rating of 4500 W. Capable of growing up to 10 crystals under both fixed and rotating magnetic fields it is scheduled for use in a joint Russian-German project. Again, this author was unable to find any details about work done with this furnace. It is reasonable to assume that experimental land based furnace designs were used prior to the development of these space furnaces, but no published work has been found on such equipment.

In October of 1991 the unmanned PHOTON 7 space mission carried the Soviet built ZONA 4 furnace into space to grow CdTe in micro gravity[27]. Two crystals were grown, the first had 50-mm of feed material grown on a 15mm long seed under the influence of a rotating magnetic field for 100 h. The other crystal had 25 mm of feed material grown on a 15-mm long seed for 50 h without any magnetic field. Both crystals were pulled at a rate of 0.27 mm/h (6.48 mm/day) and grown at 750°C. The magnetic induction was 2 mT with a frequency of 400 Hz. Changes in axial resistivity were lowest in the crystal grown in micro gravity with the rotating magnetic field when compared to growth with and without gravity and magnetic fields.

In 1994 Salk, Fiederle, Benz, Senchenkov, Egorov, and Matitioukhn reported the results of research using ZONA 4 to grow CdTeSe in micro gravity[28]. A crystal was grown with a 0.27 mm/h (6.48 mm/day) pull rate for 100 h (4.2 days). For the first 50 hours of growth a 2 mT magnetic field rotated at 400Hz frequency. The field was turned off for the second half of the growth. The crystal was much more homogeneous in the first half of its length, which also had less dispersion in its resistivity measurements when compared to all other crystals grown with or without gravity.

Senchenkov, Barmin, Tomson, and Krapukhin ran a series of ground-based experiments growing CdHgTe in ZONA 4 with and without rotating magnetic fields. Their findings, published in 1998, stated that crystal composition uniformity was greater with the 400 Hz rotating magnetic field between 2 to 6 mT compared to crystals grown with no field.[29].

1.9 Cadmium Zinc Telluride (CdZnTe)

1.9.1 Applications

There are three main areas of interest for CdZnTe. The first is as a substrate for HgCdTe infrared detectors[30]. Secondly, as a detector in high-resolution x-ray computed topography[31], and lastly CdZnTe has great promise as a gamma detector for use in nuclear medical imaging and other radiation detection devices.[32]

The fabrication of CdZnTe was first established for use as a substrate material for HgCdTe infrared detectors. This state of the art detector forms the focal plane arrays used in Nag missile guidance systems, and plays an important role in military systems used in target acquisition, identification and tracking. For this reason the production of CdZnTe has received attention from bodies like the Defence Research & Development Organization (DRDO) in the United States. The DRDO is developing production centers for CdZnTe to achieve self-reliance in what they believe to be a "critical material"[33].

X-ray diagnostics measure the intensity of a transmitted x-ray beam to create images. The standard technique of irradiating the patient with an x-ray beam and producing the image on photographic film is well known and used. However, with the use of radiation detectors, computers and image processing techniques, photographic film can be replaced by computerized tomography (CT) radiographic imaging systems. One of the advantages of such a system is a substantial reduction in processing time allowing the image to be viewed almost immediately. Also, with CT radiographic imaging it is possible to produce consecutive two-dimensional slices of a three-dimensional object. This is a great improvement over standard x-rays where a complete picture of an object is possible but not a slice or section. There are several different materials of interest for CT scanning, including CdTe, CdZnTe, CsITi, and $CdWO_4$. Preferred crystals can vary depending on applications. CdZnTe has been used successfully in some applications though its use is limited by a long after glow[34]. At the Oak Ridge National Laboratory a prototype singlepixel CdZnTe detector has had good success in identifying mutagens in lab mice[35], most CdZnTe x-ray detectors remain in the research and development stage[36].

Materials used for gamma ray detectors require two properties. The first is efficient gamma absorption. Heavier elements such as Cd and Te have better absorption than lighter ones like Ga and As that have been traditionally used as gamma detectors. The second property required in a detector is efficient collection of the electrical signal generated by absorbing a gamma photon. This property is related to the energy band gap of a material. Energy band gap is a measure of the energy required to mobilize electrons in a material. Therefore the energy band gap of an electric conductor would be zero and that of and insulator large. With semiconductors, some electrons can move by virtue of energy from thermal vibrations. In gamma detector electrons moving due to thermal vibrations creates a signal known as "electrical noise". This noise is superimposed over the signal created during the gamma absorption process and leads to signal degradation and poor resolution. Both Ge and GaAs have a low energy band gap and must be cooled to cryogenic temperatures to reduce thermal vibrations and electrical noise in order to obtain reasonable resolution. This means that any Ge or GaAs based gamma detector will have the size, complexity and cost of a cryogenic cooling system associated with it. CdZnTe has a large energy band gap and high thermal conductivity at room temperatures, so no cryogenic refrigeration is required. It is also more sensitive than Ge or GaAs to gamma rays. This means that for medical applications, patients require lower doses of radioactive isotope. This makes CdZnTe ideal for use as a gamma ray detector. The greatest limitation to the wide spread use of CdZnTe is the availability of large numbers of homogenous single crystals. This is due to the material's thermal properties that make it difficult to grow. One other material suitable for gamma-ray detectors is HgI_2. Because of the high volatility of both Hg and I this crystal is very difficult to grow in single crystal form and has only been done by condensing the elements from vapor. Vapor growth is typically costly and slow making HgI_2 an unattractive alternative considering the large volumes of crystals needed in gamma detectors.

One of the principal applications of gamma ray detectors is for Gamma-ray cameras used in nuclear medical imaging.(NMI) There are several advantages of nuclear medical imaging over other imaging procedures such as general radiology, CT and magnetic resonance imaging (MRI). These technologies are able to produce a two-dimensional picture and in some cases consecutive slices of a three-dimensional object but not the full three dimensional picture that is possible with nuclear medical imaging[37]. Also with nuclear medical imaging it is possible to measure the function of a body, not just its anatomy. An example of this is assessing a gallstone. There are different ways to determine the size and the exact location of a gallstone, but only NMI techniques can conclude whether or not the stone is inhibiting the movement of fluid in the gallbladder[38]. To produce an image a radioactive pharmaceutical is injected or taken orally by the patient. This radiopharmaceutical is tagged to a compound that has an affinity for the organ of interest. A gamma-ray camera is then used to create an image or scan of the distribution of the radiopharmaceutical. Radiologists look for absences or excessive distribution, indicating a diseased area. There are two basic layouts for nuclear medical imaging cameras. The conventional system uses NaI crystals that produce small flashes of light known as scintillations when impacted by a gamma ray. The first scintillation type cameras (still widely used today) was developed in 1958[39]. Photomultiplier tubes pick up the scintillations and convert the light signal to an electric current. This current is converted to a digital signal that is interpreted by a computer algorithm and displayed. A CdZnTe, GaAs or Ge camera produces a digital signal directly from the impact of a gamma ray with the crystal. This signal can be fed directly to the computer algorithm with minimal signal processing. This is a more efficient process than conventional gamma cameras allowing lower radioactive isotope doses to be used. The removal of the photomultiplier tubes from the system also decreases the size, weight and cost considerably.

There is a wide range of other applications for gamma ray detectors. Geo-steering is a method of drilling for oil where a gamma ray counter measures the radioactivity in the drilling slug. With knowledge of the radioactiveness of different rock types, drill heads can be more accurately steered toward oil reserves[40]. Since CdZnTe based gamma ray detectors would not require any bulky cryogenic refrigeration systems, they would be transportable and ideal for monitoring radioactive waste storage or verifying nuclear treaties[41] [42]. Another interesting application is gamma ray astronomy, where astrophysicists hope that the unprecedented accuracy of CdZnTe gamma ray detector arrays will unlock the mysterious source of gamma ray bursts[43].

Material	Band Gap (eV)	Resistivity (Ohm-cm)
CdZnTe	1.56	10^9 to 10^{10}
CdTe	1.47	$8.3*10^3$
HgI_2	2.13	
GaAs	1.42	10^7 to 10^8
Ge	0.67	47

[44, 45 46]

Table 1 Some Properties of Gamma Detector Crystals

1.9.2 Production

CdZnTe is produced commercially by several companies, each one having its own specific set of growth techniques. The specifics of a company's chosen techniques are kept secret and will not be discussed here. High Pressure Bridgman is by far the most popular method for bulk production of CdZnTe. In the United States companies such as eV Products and Digirad use this method[47] [48] as well as many experimental institutions such as The Institute of Single Crystals in Khainr, Ukraine, and Institute of Solid State Physique in Moscow, Russia [49] and University of Victoria's Crystal Growth Research Group in Victoria, Canada. Vertical Bridgman is also used by eV and Keystone Crystal cooperation. The latter company is also known to use Czochralski growth for CdZnTe[50]. There is also ongoing research into the use of Vapor Growth, THM and LPEE, but there is no known production by these methods.

1.10 Purpose and Outline

The objective of this thesis was to design and build a furnace capable of growing one-inch diameter CdZnTe crystals while varying a number of growth parameters. The furnace was to allow a researcher to grow the required experimental crystals so that optimal growth parameters can be found to maximize crystal quality and speed of growth. The different growth parameters that can be obtained with the furnace are as follows.

- Temperatures between 750 and 950 ^{o}C
- Linear translation rates between 1 and 10 mm/day
- Temperature gradients between 100 and 1000 ^{o}C/cm
- Rotating magnetic fields between .5 and 2 mT and 5 to 150 Hz
- Fixed coaxial magnetic field between 0 and 2 T (added in the future)
- The application of acoustic wave mixing (added in the future)

This thesis contains

- An overview of crystal growth techniques.
- An outline of the uses of CdZnTe.
- A Summary of the work done on the use of the THM.
- Description of the thermal modeling work done on THM design at the University of Victoria
- Description of the THM furnace design and operation at the University of Victoria
- Conclusion and future Improvements

2 Thermal Analysis by the Finite Element Method

2.1 Introduction

The need for a thermal model of the THM furnace stems from the importance of temperature gradients in crystal growth. The commercial software Ansys 5.7 was chosen for its reliability, speed and availability at the University of Victoria. There is a lack of knowledge of the optimum growth conditions for THM crystal growth. This means that the model needs only to give a general idea of the temperatures that the crystal and growth solution would be subjected to. Any further accuracy would be superfluous. For comparison, a model was developed for an existing THM furnace design that is used by Amistar Research and Development Inc. of Victoria to grow CdZnTe. It was felt that the performance of this furnace could be improved by increasing the temperature gradient between the hot (middle) and cold (bottom) zones[51], see Figure 6 in the first chapter. Three models will be presented here, the first is a two-dimensional model of one half of the Amistar furnace, the second is a similar model of a proposed sloped cooling block design. The final model is of the layout chosen for the THM-1 furnace. It incorporates the extended cooling block seen in the second model with more insulation and less unnecessary heating of the cooling block.

2.2 Model Development

Several trials of three dimensional models were made. They were found to be slow on the available computers (Pentium 200MHz, 64MB RAM) and almost exhausted the computation power of the student version Ansys 5.7 software being used, even at course grid sizes. All models were therefore done in two dimensions. This introduces some inaccuracy into the model.

Some assumptions were made to simplify the model. It was assumed that all sides of the furnace were adiabatic except the areas around the heater and the outside face of the cooling block, where heating and cooling are supplied to the furnace. These areas have known temperatures that will be fixed by applying loads. They are also the areas with the highest heat fluxes and will have the greatest effect on the temperature profile. The top and bottom of the furnace as well as the outside of the insulation were assumed to be adiabatic. This is an assumption that will introduce some inaccuracy into the model. However, since the most important information is the temperature gradient in the center of the furnace the effect of heat transfer on the outside of the furnace would produce little change. It was also assumed that the inside surface of the furnace would be adiabatic, this is a poor assumption since there is a high temperature gradient present here and the liquid metals in the charged ampoule would have an effect on the temperature distribution. There are two reasons that this simplification was made. The first is because of the difficulty in modeling the interactions between the crystal and both the hot and cold areas of the furnace. Inside the ampoule there are phase changes and convection currents (possibly coupled with magnetic field currents), the modeling of which is far beyond the scope of this thesis. There is radiation and convection between the furnace and the ampoule, both of which are difficult to model and are dependent on the condition at the surface of the ampoule. The second reason that the inside of the furnace was assumed to be adiabatic was that furnaces are sometimes "characterized" by running a thermocouple up the inside of the furnace while it is running at operating temperatures loaded with an empty ampoule. The purpose of this characterization run is to get some idea of the temperature profile of the furnace enabling comparisons between furnaces. The empty ampoule reduces convection and helps to create a standardized method. Characterization runs also produce data that is used for modeling the interactions inside the ampoule. The temperature profiles that are generated from the characterization are superimposed onto a model of the ampoule charge. The model calculates fluid motion, phase change, and concentrations inside the ampoule charge. It was therefore felt that modeling the furnace under characterization type conditions would be useful on a comparison basis. The contact resistance between all the components of the furnace were also neglected. It was felt that this would not introduce a large error relative to some other approximations that were made.

Loads were applied to the furnace by fixing the temperature around the areas that would be in radial contact with the heater to 1170°K (896°C) and the outside surface of the cooling block to 303°K (30°C). This was the simplest way to accurately portray how the furnace will be run. In the real furnace the heater is in contact with a thermocouple. Therefore the thermocouple reading is the same as the heater. In the model the temperature is applied directly to the walls surrounding the heater; this temperature would be lower than that of the heater. Since the furnace will be run at temperatures between 750 and 950 °C this difference is not considered important. The cooling block will be cooled to maintain a constant temperature at a decided level. One advantage of the furnace design is its ability to change the temperature of the cooling block. This allows experiments comparing crystals grown under different temperature gradients. The model fixed the outside temperature of the cooling block at 30°C since this is a reasonable value and one that can be compared to existing Amistar THM furnaces.

2.3 Mesh Generation

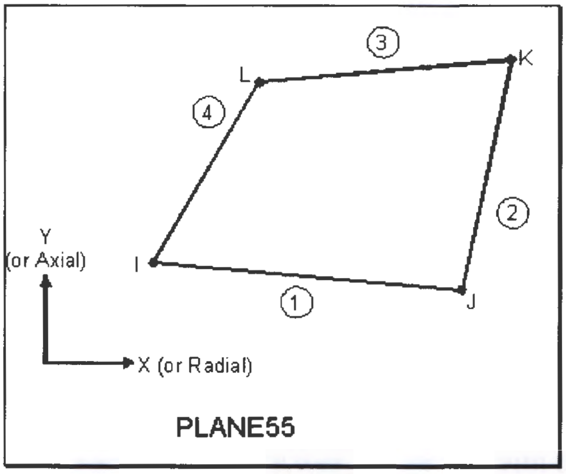

Figure 12 Ansys PLANE55 Planer Element

Initially two different Ansys planar elements were used to mesh the models. The first, PLANE 55 is a two-dimensional linear thermal conduction element with four nodes and a single degree of freedom, temperature, at each node. The second, PLANE 77, is a higher order 8 node thermal conduction element. It also has one degree of freedom, temperature and is well suited for modeling irregular shapes. It was found that the linear PLANE 55 gave efficient results with the shapes modeled and a reasonably coarse grid. A comparable grid with the higher order PLANE77 took longer to solve and gave similar results. For this reason PLANE 55 was used for most of the models.

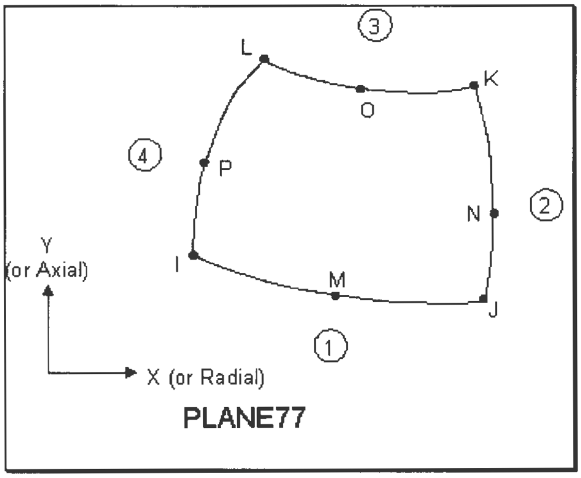

Figure 13 Ansys PLANE77 Planer Element

Meshing size was contorted by the Ansys "ESIZE" command. This command divides the length of each surface boundary by a given length, (rounded upward to next integer) then divides the surface boundaries by the number calculated. This makes each surface boundary divided into lengths that are equal to or smaller than the length defined by the ESIZE parameter. Most runs were done with an ESIZE length of .002 (2mm) this produced 1429, 1232 and 1326 elements and 5476, 3912 and 4190 nodes in the three models respectively. Some models were run with ESIZE length set at .001 (1mm) (approximately 5284 elements) to make result comparisons and ensure fine enough grid spacing. No noticeable differences in results were observed with the finer grid.

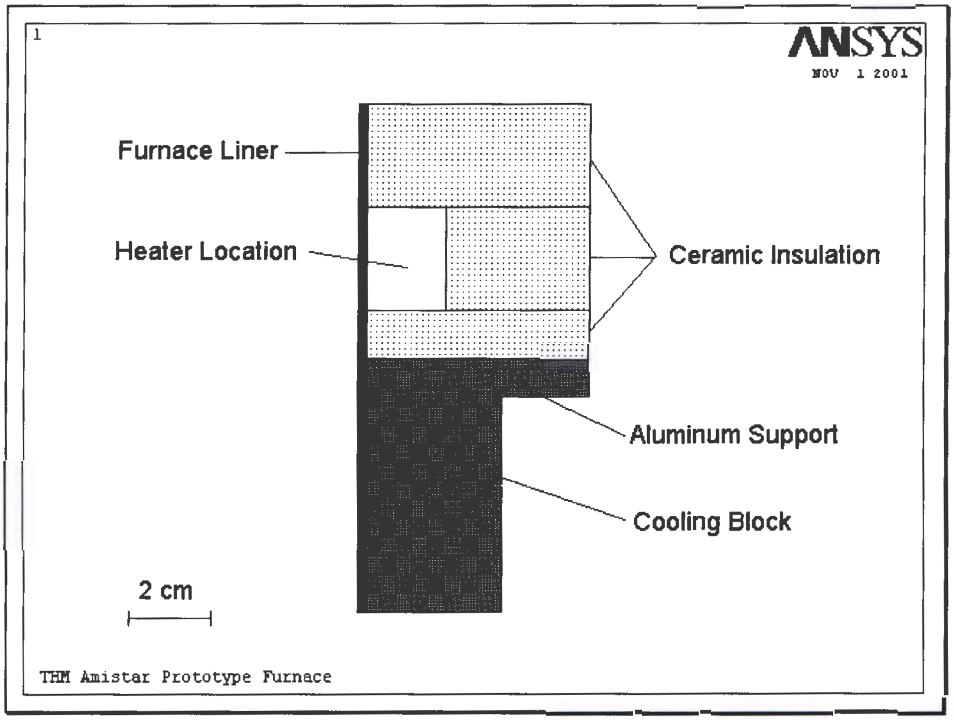

Figure 14 Computational Domain of Amistare's Prototype Furnace

2.4 Models Description

As has been stated three models were made and tested. The first can be seen in Figure 14. This model is based on the furnaces used to grow CdZnTe at Amistar Research. The model is narrower than the Amistar design to accommodate the six rotating magnetic field coils, and still have a small enough diameter to fit inside the fixed magnetic field generator. The model will be used for comparison with other models. In Figure 14 the black area represents the furnace liner, a quartz tube that runs the length of the inside of the furnace. The gray area represents the aluminum cooling block and some aluminum support structure. All dotted areas are ceramic insulation. A hole is left in the center of the model representative of where the resistance heater will be placed. Loads are placed on the four sides of this hole labeled "Heater Location".

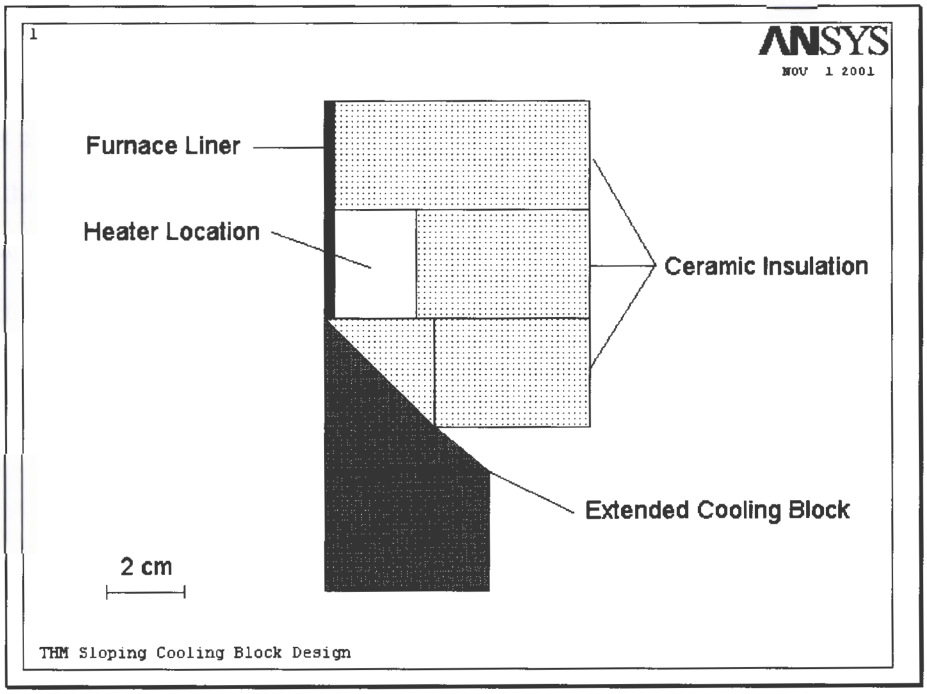

Figure 15 Sloping Cooling Block Design

The desire to grow crystal under a higher temperature gradient brought about the idea of the sloping cooling block, seen in the model in Figure 15. A model was made of a proposed design which brings the cooling block closer to the heater and decreased the amount of insulation between the heater and cooling block along the inside liner of the furnace. Since results of the first model showed considerable spreading of the temperature through the quartz furnace liner, the liner was shortened. In the proposed design the liner runs up from the top of the cooling block. This means that the cooling block is in direct radiant contact with the ampoule. It was necessary to keep the liner between the ampoule and the heater to prevent growth material from coming into contact with the heater if an ampoule breaks. For model simplicity the furnace liner does not make full contact with the cooling block but sits on a lip, also, some of the aluminum support structure was neglected. The liner placement could have a significant effect on the temperature profile that the ampoule sees. The support structure would have an effect on the temperature profiles in the furnace but it is not considered significant in the region of the ampoule. Because of other shortcomings this design was modified before a more accurate model was made.

selected convergence criteria of 10^{-6} and the initial time step was set to two. The algorithm automatically increases the number of time steps if large load increments are obtained. The automatic time steeping algorithm was used exclusively and is thought to give good convergence for these simple problem[53]. A variety of load step factors were set using the Ansys "NSUBST" command. Higher numbers of load steps significantly increased the computational time with no noticeable effect on the results. For this reason a load step of one was used almost exclusively.

2.6 Results and Discussions

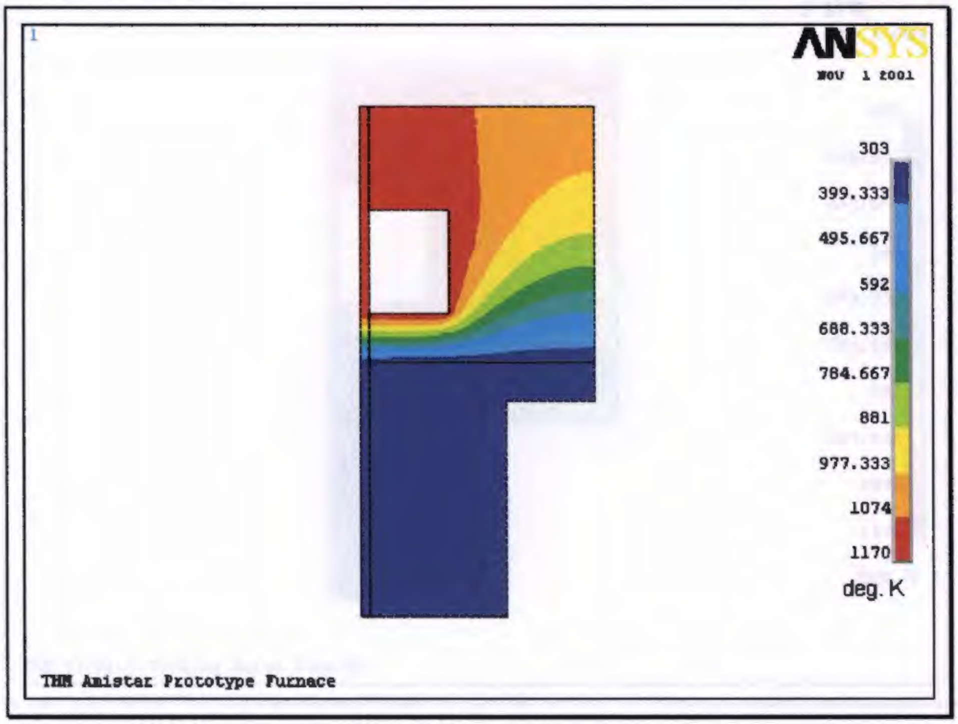

Figure 17 Isothermal Plot of Amistar Furnace Design

Isothermal plots of the models can be seen in Figure 17, 18 and 19. There is a larger thermal gradient between the cooling block and the heater in Figure 18 and 19 compared to Figure 17. This indicates that the latter designs will be successful in producing steeper temperature gradients between the heater and the cooling block, which were discussed in the introduction of this chapter. Close inspection of the isotherms also shows them "spreading" as they enter the quartz furnace liner (in black in Figure 14, 15 and 16). This undesirable smearing of the temperature gradient was partly eliminated by removing the lower half of the liner, in the second and subsequent models.

Figure 20 is a comparison of the temperature profiles of the Amistar furnace (Figure 14 and 17) and the final design (Figure 16 and 19). This graph was made from the nodal solution along the inside surface of the two dimensional models. The higher temperature gradient between the hot and cold zone in the latter design suggests the new furnace will improve the growth conditions of the crystal compared to the prototype Amistar design.

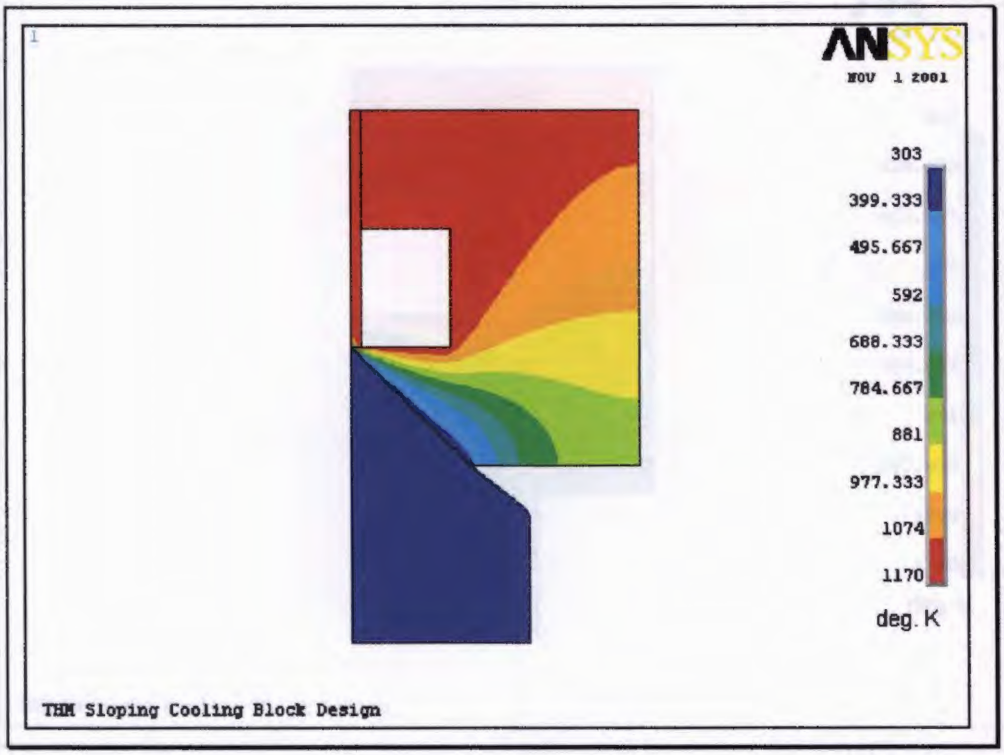

Figure 18 Isothemals of Sloping Cooling Block

Figure 21 is a plot of the temperature along the axis of both the Amistar Prototype and the final THM design. This information was obtained by ramping the furnace up to a set point temperature and allowing it to stabilize. A type K thermocouple was moved along the inside wall of the furnace and readings were taken every centimeter. In order to limit the effect of convective heating or cooling blocks of insulation were cut to fit inside the furnace liner. These blocks helped hold the thermocouple against the wall of the furnace and helped suppress air movement. A similar procedure was used with the Amistar furnace except no blocks were used. The top and bottom of the furnace liner was sealed to reduce convection and the thermocouples were feed through the top cover and ran along the wall of the furnace liner. As can be seen from the figure, the gradients are higher in the new furnace than the Amistars prototype. This was expected from the numerical studies and shows that the model adequately predicted the effect of design changes relative to the prototype design.

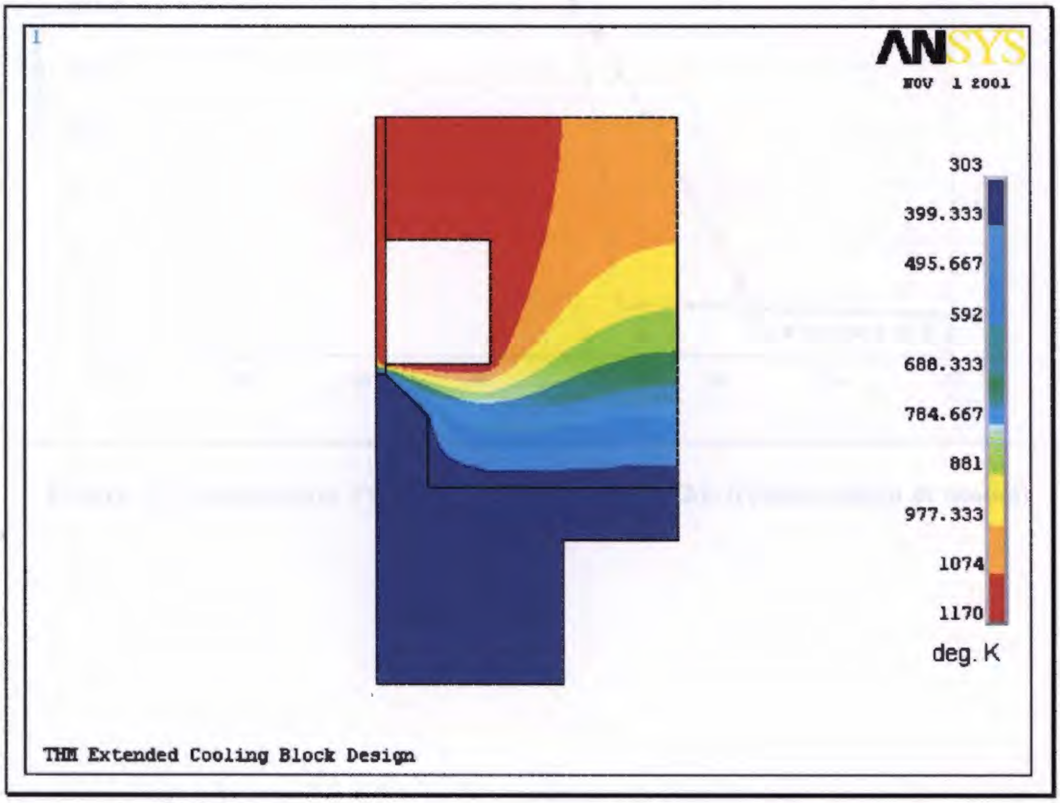

Figure 19 Isothermals of Final Extended Cooling Block

The models made using Ansys 5.7 and the finite element method were useful in determining the effect on the temperature profile of different cooling block shapes. Even though the temperature profiles that were obtained may vary considerably from reality due to some of the assumptions made to simplify the model, the results were still useful in determining the effect of shortening the furnace liner and incorporating different shapes of tails on the cooling block. The cross-sectional layout shown in Figure 16 will be used as a basis for the furnace discussed in the subsequent chapter.

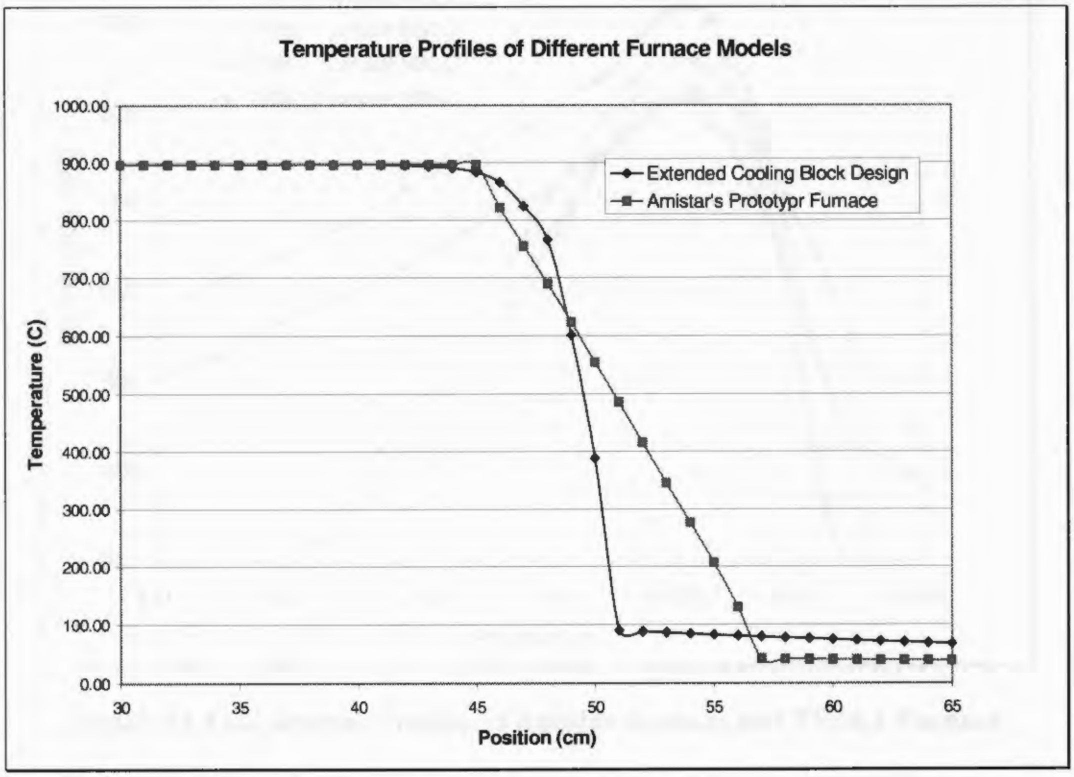

Figure 20 Temperature Profile of Amistar and THM-1(values taken at model)

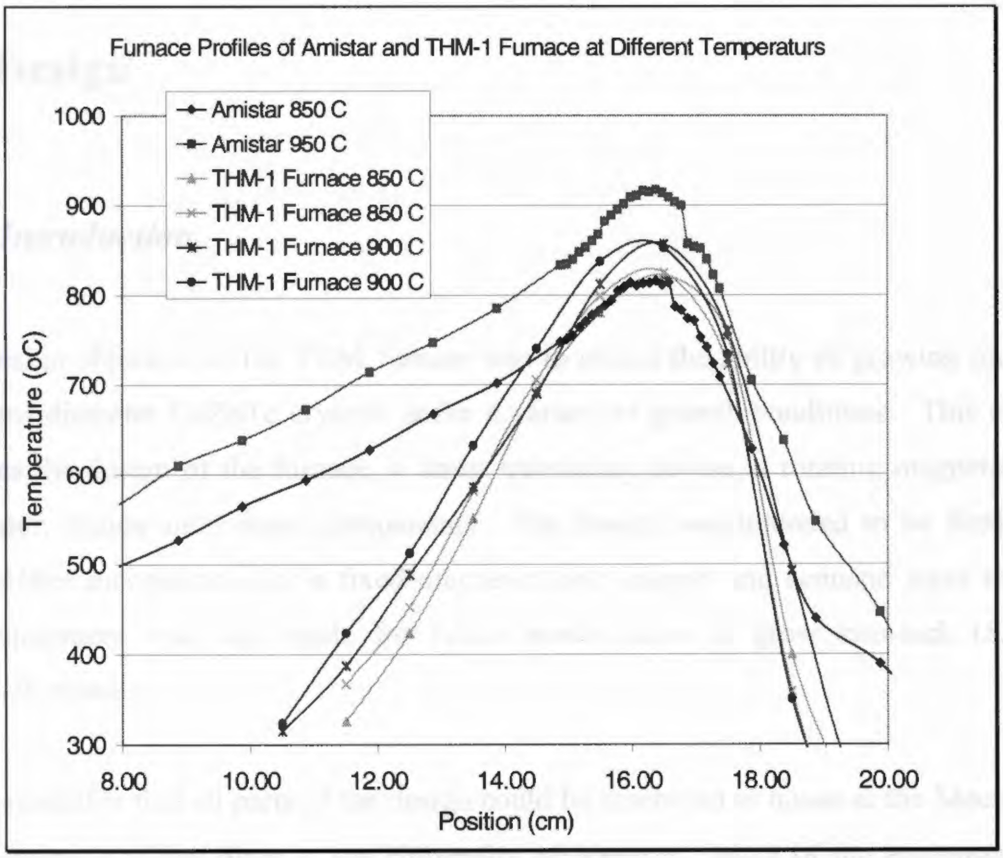

Figure 21 Temperature Profiles of Amistar Furnace and THM-1 Furnace

3 Design

3.1 Introduction

The design objective of the THM furnace was to obtain the ability of growing one inch (2.5 cm) diameter CdZnTe crystals under a variety of growth conditions. This chapter outlines the design of the furnace, a linear translating device, a rotating magnetic field generator, stands and related components. The design was intended to be flexible to enable later incorporation of a fixed magnetic field magnet and acoustic wave mixing. The equipment was also made for future modification to grow two-inch (5.1-cm) diameter crystals.

It was desirable that all parts of the design could be machined in house at the Mechanical Engineering Machine Shop at the University of Victoria. Most of the equipment was therefore made from aluminum. This material is reasonably priced and easily machined with the available equipment. Aluminum is also a nonmagnetic material, which is an important consideration since the furnace will be in a high magnetic flux. The furnace is assembled almost entirely of 10-32 screws. This standardized screw size makes assembling, maintenance and modification simpler. Screws that were positioned inside the proposed bore of the fixed magnet were made of stainless steel, to prevent any unwanted forces acting on them and distortion of the magnetic field.

3.2 Linear Translator

The requirement for the linear translator is that it moves the ampoule through the furnace at constant steady speed while transmitting no unwanted vibration to the growth ampoule. The ampoule will need to be moved between 1 and 10 mm/day downwards and also be able to be positioned quickly between crystal growth runs. The approach used was to build two separate apparatuses; a lead screw translator, and a motor driver with a gearbox. A belt was used to transmit power between the gearbox and the lead screw, this enabled the motor and gearbox to be vibration isolated from the lead screw. A prototype lead screw translator and motor driver were built and tested prior to the completion of the furnace and furnace stand. These prototype components were successful and later mounted onto the furnace stand.

A single axis translator was needed with smooth motion, which could move at very low speeds. Since most electric motors work best at higher speeds a translator with the lowest translation rate for a given input rotational speed was designed. The design made use of a lead screw (3/8-16-1st) with a lead of 0.0625 in per revolution (1.59mm/rev). A matching Teflon nut was mounted on a carriage that moved along two precision ground 1/2-in. steel shafts. These shafts are mounted at the top and bottom to a backing plate. The single axis translator can be seen in Figure 22.

Power transmission from the motor to the lead screw is made by a direct drive coupling to the 625 to 1 gearbox and then belt driven on a 6 to 1 ratio to the lead screw. W.M.Berg Inc. supplied the gearbox. It has a gear ratio of 625 to 1, a maximum speed of 5000 RPMs and maximum output torque of 600oz.in.(4.24 Nm). Constructed of stainless steel and aluminum with bronze bushings in an anodized aluminum housing, it has a 30 min. maximum backlash on the output shaft. This gearbox was chosen as a simple reliable method of increasing the speed of the motor.

A belt drive was used between the gearbox and transition to aid in vibration isolating the lead screw. A gear ratio of 6 to 1 was used since it was the maximum available for the belt and pulleys used. W.M.Berg, Inc also supplied these. The 1/8-inch (3.18 mm) belt is made of Polyurethane with a 0.018-inch (0.46-mm) stainless steel cable core. It can operate with up to 5 pounds load and a maximum speed of 1800 RPM. The pulleys are anodized aluminum with a 1/4-inch (6.35 mm) bore and a 1/8 inch (3.18-mm) track.

Several types of motors were considered, mainly stepper and servo as well as fixed speed AC and variable speed DC. Servomotors can move at precise speeds that do not change with fluctuations in loads within their operating range. They do require the use of motor driving circuits and an encoder. Stepper motors also need driving circuits, but do not require the use of an expensive encoder. The disadvantage of stepper motors is that they move in incremental steps that lead to jittery movement or cogging especially at lower speeds. Servomotors can also have jerky movement but only at very slow speeds. It was difficult to get any information from motor manufactures as to the performance and smoothness of their motors at the low speeds. Most motor applications require torque and positioning accuracy, and low speed smoothness is not important. This was one of the reasons that a prototype was made and tested. Both AC and DC motors have a cost advantage over other types. Slow AC motors (clock or timer motors) require no connecting circuitry and can be directly connected to a 110V 60Hz power supply. DC motors require very little circuitry and can operate at a variety of speeds both forwards and backwards.

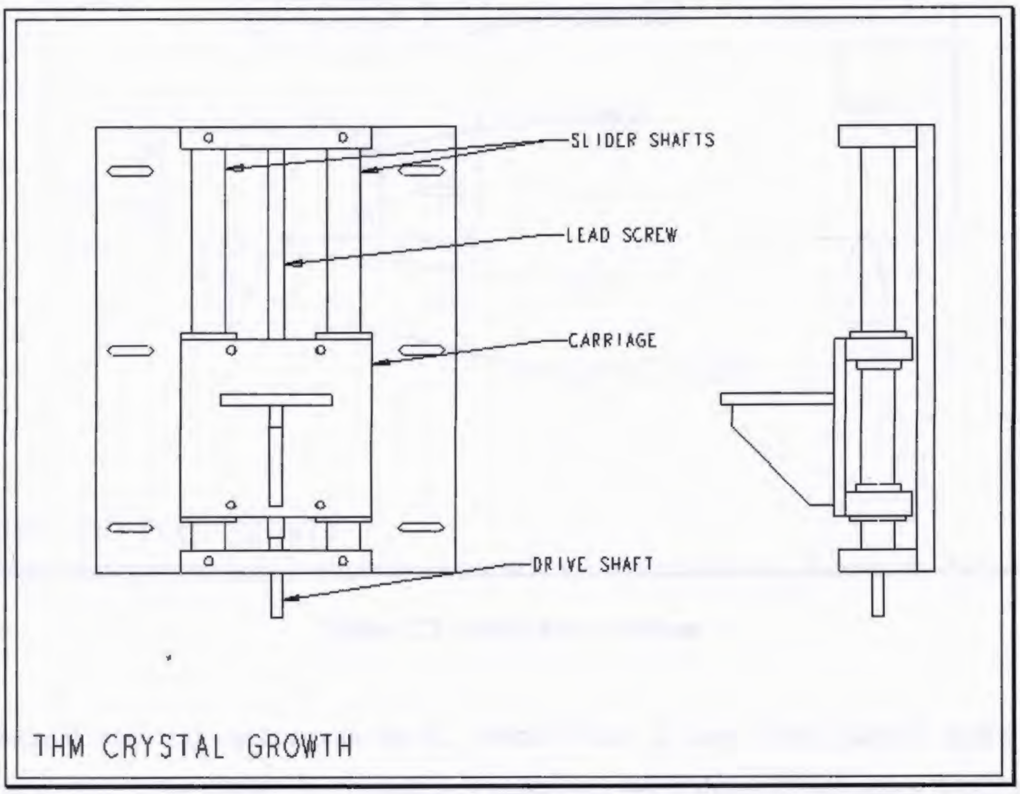

Figure 22 Linear Translator

Two motor systems were designed and built. This will allow the operators to test both systems and use the one that is the most successful, providing the most flexible design. Both systems make use of a fast moving positioning 24V DC motor. This makes it possible to quickly position the ampoule in the starting position in preparation of a growth run. This DC motor drives the lead screw directly. The first system uses a stepper motor to lower the ampoule. The motor speed is reduced by 3750 to one. This means that the motor must turn between 1.6 and 16 RPM to move the translator between 1 and 10 mm/day. At these faster speeds the cogging of the stepper motor is hard to detect. It is still an inherent property of stepper motors that they move in steps, therefore a second drive motor was also supplied.

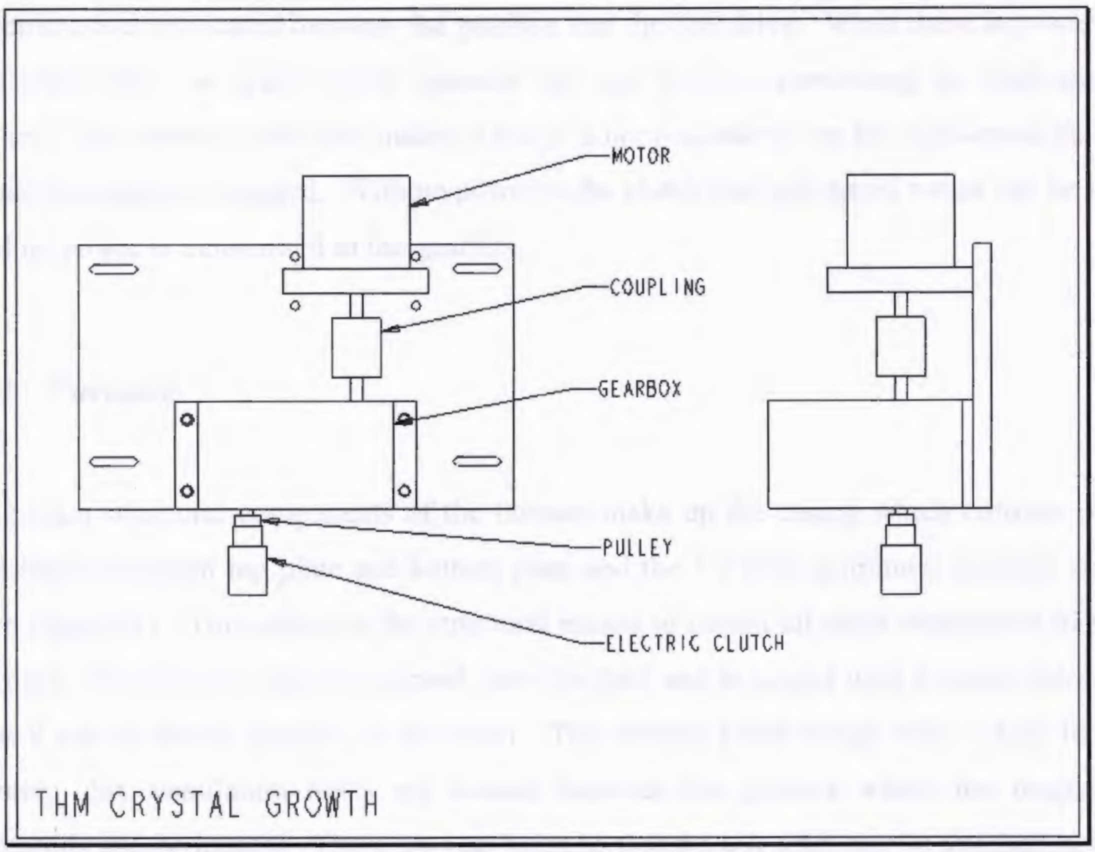

Figure 23 Motor and Gearbox

The second lowering motor was an AC clock motor. It came with built-in gears of an unknown ratio. The output shaft turns at a constant rate of three RPM with a 110V 60 Hz power supply (no load). When attached to the same 3750 to 1 gearing this motor lowers the ampoule at 1.845 mm/day. This motor is smooth in operation but lacks the flexibility of the stepper motor. If other translation rates were desired they could be achieved by using a different motor or changing the belt drive ratio. AC clock motors are reasonably priced and can easily be salvaged from a variety of old equipment. They come in a number of different fixed speeds. By varying the belt gearing between the existing 6 to 1 gear ratio and a 1 to 1 ratio, speed between the existing 1.85 mm/day and 11.08 mm/day could be achieved, covering almost the full range of the desired 1 to 10 mm/day.

Since there are two motors connected to the same drive system it was necessary to incorporate a clutch to disengage one of the motors while the other is operating. A 24V electric clutch is located between the gearbox and the belt drive. When there is power to the clutch the low speed motor operates the lead screw, overrunning the high-speed motor. The control circuit was made so that it is not possible to run the high-speed motor while the clutch is engaged. With no power to the clutch the high-speed motor can be run and no power is transmitted to the gearbox.

3.3 Furnace

The main structural components of the furnace make up the casing which consists of a 1/2-inch aluminum top plate and bottom plate and the 1/2-inch aluminum cylinder shell (see figure 24). This casing is the structural means to mount all other component of the furnace. The bottom plate is mounted onto the shell and is tapped with 6 screw holes so that it can be bolted directly to the stand. The cooling block hangs from a hole in its center. Six ventilation holes are located between the potions where the magnetic solenoids will be located. There are also holes so that the solenoids can be attached to the bottom of the furnace. This will prevent them from moving and help provide good thermal contact between the bobbins and the furnace bottom, helping to keep the magnets cool. The furnace shell maintains the alignment of the cooling block and the top plate. There are two tapped holes for attaching the ground wire to the inside of the furnace.

Nothing attaches to the outside of the shell as this could interfere with the permanent magnet that will sit around the outside of the furnace. The top plate has a large center hole where a marinite (ceramic) cap locates the furnace liner. This cap is held in position by three aluminum positioning blocks. The blocks are bolted to the top of the plate and are adjustable. Six terminal blocks are placed around the outside of the top plate to connect the magnet solenoids to their power supply with accompanying holes to pass the wires through. The top plate also has a plug for the heater power supply, ventilation holes and a handle mounted.

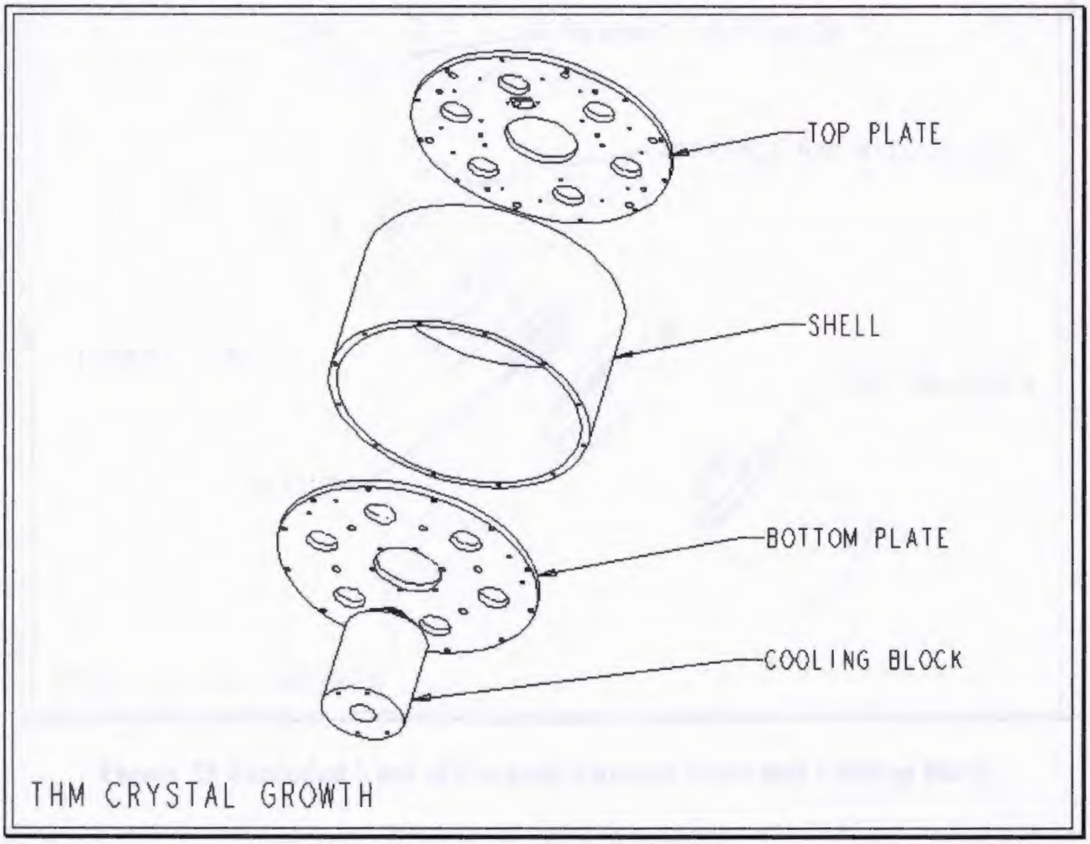

Figure 24 Cooling Block and Components of Furnace Casing

The cooling block is an integral part of the furnace since its shape and position will change the temperature profile that the crystal will grow in. A copper tube with cooling fluid pumped through it will provide cooling to the outside of the block. The block has thick walls, and all boltholes are close to the outside to increase axial temperature symmetry near the location where the crystal will grow.

The center bore of the furnace is lined with a quartz tube or furnace liner. This liner keeps the cooling block, heater, and all ceramic insulation in place so there is a smooth obstacle-free path for the growth ampoule to pass through. There is a small lip in the top of the cooling block that the liner fits into and a marinite cap on the top of the furnace that the liner passes though. This cap can be adjusted to ensure concentricity between the cooling block and liner.

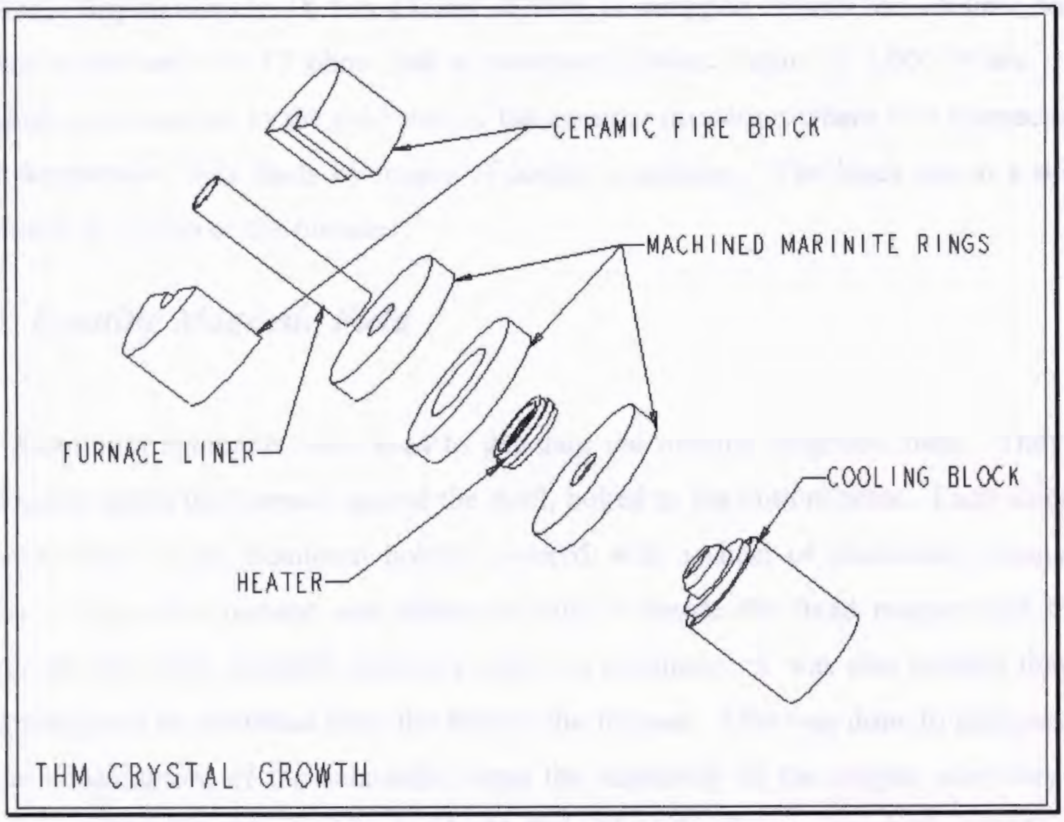

Figure 25 Exploded View of Ceramic Furnace Parts and Cooling Block

Two types of ceramic insulation were used in the furnace. Marinite is a calcium silicate material made of fibers, micro silica and binders. It is highly damage resistant and machinable[54]. Marinite was used around the tail of the cooling block and the heater since it can be machined into the irregular shapes needed, withstand the high temperature in this region and lasts well even under conditions of high temperature gradients and thermal cycling. In the lower temperature area above the marinite, ceramic firebrick was used. This less expensive material can not be machined. It was cut with a band saw to rough tolerances (1/8-in. or 3mm). Since this area does not directly influence the temperature where the crystal will be grown it is not as crucial as around the heater.

The heater used in the furnace is designed and built by Amistar. It is made of a machinable ceramic that, once machined and fired, is hard brittle and thermally stable. The Torus shaped heater has a line of teeth around its inside where resistance wire is wrapped. The 19 gauge Kanthal A1 wire has a resistance of 0.6770 ohm/foot (2.221 ohm/m). Approximately 18 feet (5.5m) of wire is wrapped around the ceramic heater giving a resistance of 12 ohms and a maximum power output of 1,000 Watts. The Kanthal wire runs out to the cold side of the ceramic insulation where it is connected to high temperature wire leads by means of copper couplings. The leads run to a socket mounted on the top of the furnace.

3.4 Rotating Magnetic Field

Six Aluminum solenoids were used to generate the rotating magnetic field. They are positioned inside the furnace against the shell, bolted to the bottom plate. Each solenoid is constructed of an aluminum bobbin covered with a sheet of electrically insulating Mylar. Since the furnace and solenoids must fit inside the fixed magnet (yet to be designed) their total diameter had to be kept to a minimum. It was also decided that the solenoids must be insulated from the heat of the furnace. This was done to decrease the power consumption of the solenoids, since the resistivity of the copper wire they use increases with temperature. Ms. Robbi McDonald of the University of Victoria Crystal Growth Research Group performed the calculation to find the optimum solenoid size that would generate the desirable 2 mT magnetic field. The size and position within the furnace of the six solenoids can be seen in Figure 26.

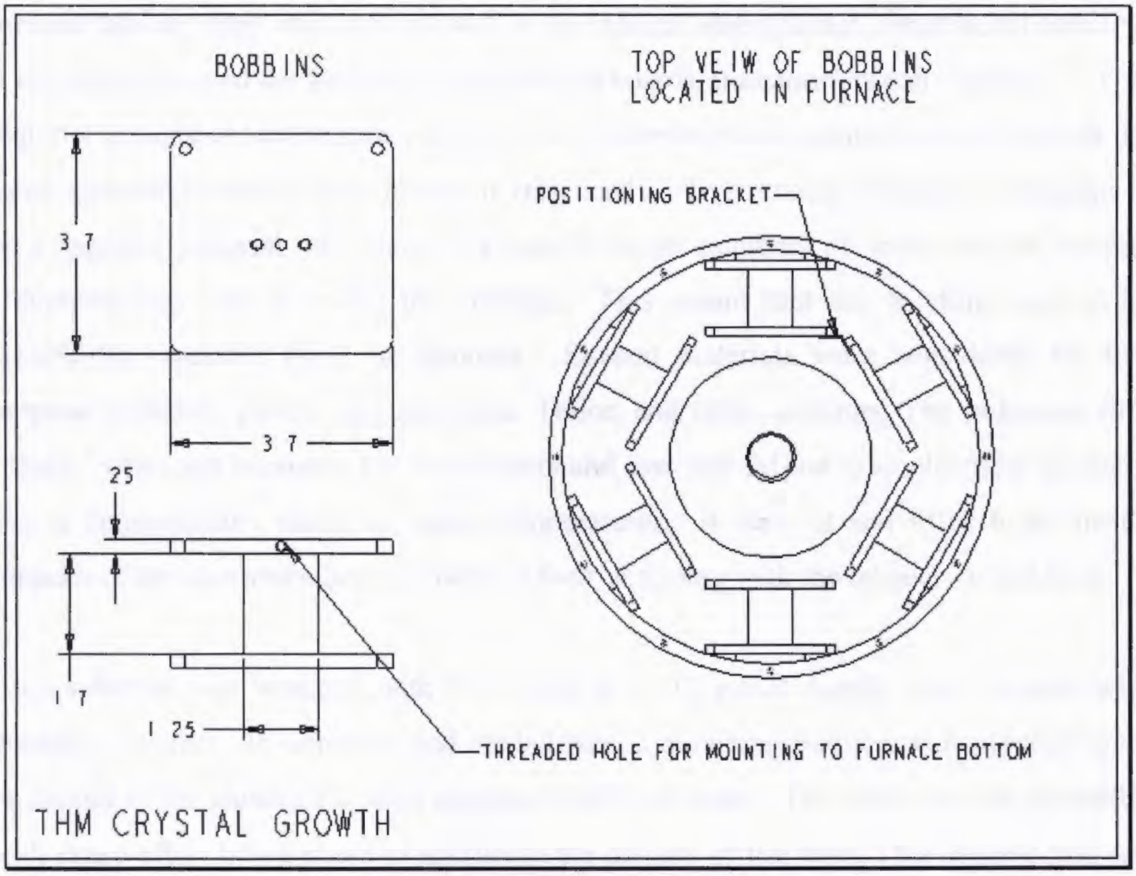

Figure 26 Bobbin Location and Dimensions

The bobbins needed to have smooth surfaces to minimize the chance of damaging the wire when they were being wound, be electrically insulated to prevent a damaged wire from shorting out on the bobbin, be thermally conductive to aid in the cooling of the solenoid, and be economical to build. Several materials were considered for use in building the solenoid bobbins. These include aluminum, iron, machinable ceramic, and plastics (Phenolic). An iron or steel core could have been used to focus magnetic fields strength. This idea was not used since the metal core would have interfered with the stronger fixed magnet with unpredictable reproductions. Machinable ceramic such as the material used to make the furnace heater could have been used. However, the higher purchasing and manufacturing costs made them impractical; they are also brittle and prone to cracking if not handled with care. Phenolic is a thermosetting industrial laminated plastic manufactured by heating and pressing layers of paper or glass cloth impregnated with synthetic resin. It is a lightweight electrical insulator that has good merchantability, heat resistance as well as mechanical strength and dimensional stability. It is commonly used for things such as terminal boards, transformers and bearings[55]. This material is suitable for the solenoid bobbins. However, most suppliers would not sell the small quantities needed, thus making it very costly. Even though Phenolic is thought to be a superior material, and should be used if larger numbers of solenoids are needed, aluminum was used to make the bobbins. This meant that the windings had to be electrically insulated from the bobbins. Several materials were considered for this purpose including paints, laquers, mica, Teflon and other coatings. The polyester film "Mylar" was used because of its availability and low cost. Mylar is an electrical insulator and is dimensionally stable at higher temperatures. It was cut and fitted to all inside surfaces of the aluminum bobbins prior to their wrapping with the lacquer-coated wire.

Each solenoid was wrapped with 830 winding of 18 gauge copper wire covered with insulating lacquer. In order to wind the bobbins, a mounting flange was made that could be locked to the chuck of a lathe equipped with a counter. The wire was fed manually, with every effort being made to maximize the density of the wire. This process was not easy, and not all of the bobbins have equal wire density. It is therefore expected that there will be some inconsistencies in solenoid performance. Also, the counter used has some reliability problems meaning that some of the solenoids may not have exactly 830 windings.

3.5 The Static Magnetic Field

The designing and building of the fixed magnet is not part of this project. It did however, have an influence on how the furnace was designed. The furnace, rotating magnetic fields, translation apparatus and all supports and stand fit inside a 12.7-inch diameter bore. This was thought to be a reasonable size for the fixed magnet inside dimension. All power supply and thermocouple leads are attached to the top or bottom of the furnace, so they will not interfere with the fixed magnet. Also all material used are non-magnetic so they will not distort the magnetic field created by the magnet.

3.6 Power Supply and Control

Power is supplied to the furnace by means of a controller built around the Omega CN3240 Temperature Controller. This unit is a dual loop Proportional-Integral-Derivative (PID) controller. This means that it uses a PID algorithm to calculate a suitable output which is dependent on the deviation of an input from the set point. The algorithm has three-control parameters that allow it to be tuned to the specific nature of the system it is controlling. The output from the algorithm is converted to a digital signal by multiplying it by the cycle time of the controller. Therefore, if the algorithm gives an output of 50 percent and the cycle time is one second, the controller will turn on for half a second then off for half a second repeatedly. The maximum current of the controller is 5 amps, therefore a solid state relay is used to increase the signal on a separate power circuit. Input to the controller comes from a type K thermocouple.

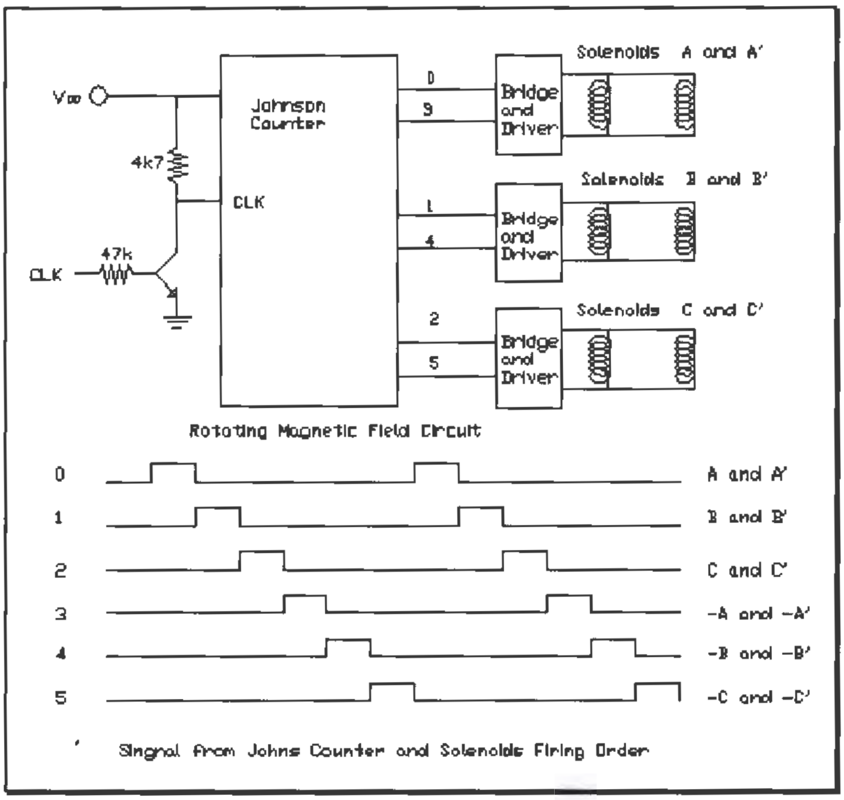

Figure 27 Circuit for Rotating Magnets

The circuit shown in Figure 27 controls the rotating magnetic field solenoids. The circuit requires the input of a clock signal and a DC power source. The Circuit-Test SWF-700 Sweep Function Generator is used to generate a square wave function that acts as a clock signal. It operates between 0.02 Hz to 2M Hz with a 0.1Amp, 5 V output with a 50-ohm load. This signal is fed into a Johnson Counter made of five D-type flip-flops. Once decoded the counter puts out the signal represented in Figure 27. The lines are grouped into (0,3) (1,4) (2,5) and fed into three driver circuits seen in Figure 28. Each driver circuit drives two magnets in parallel. The circuits are protected by diodes and will drive in opposite directions depending on which line is driven.

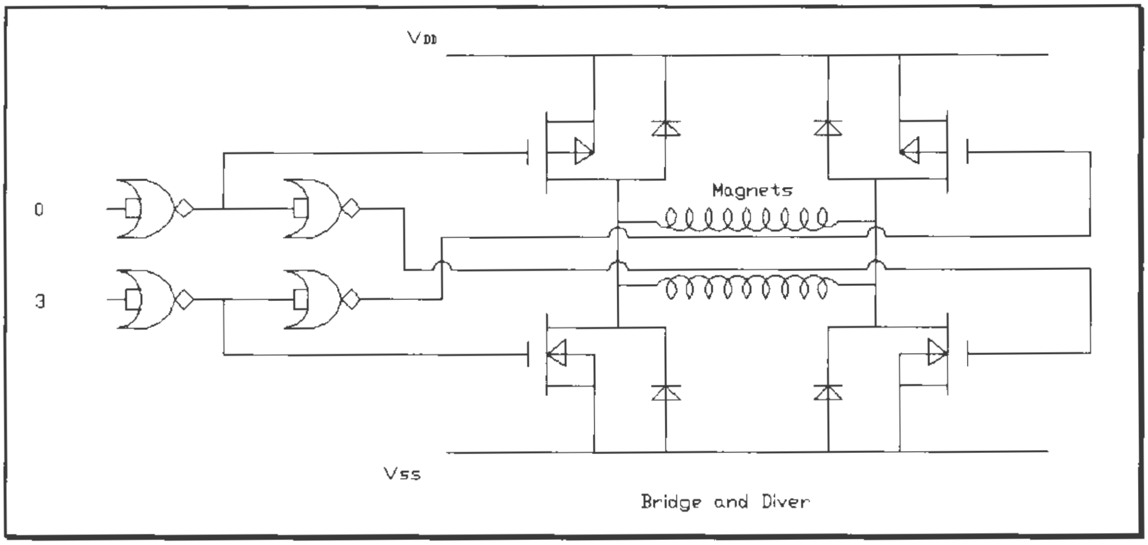

Figure 28 Bridge Diver for Solenoids A and A'

The high speed motor and clutch that engage the low speed motor of the linear translator are controlled by the 24V DC circuit shown in Figure 29. The circuit uses two end of travel (EOT) switches to ensure that the clutch and high speed motor will not transmit power to the lead screw if the carriage is at the end of its travel. An override is provided so that the carriage can be backed away from the end of travel switch, should it make contact. This override is made so that it will only work in the direction to move the carriage away from the switch. The circuit also ensures that the high speed motor and clutch will not transmit power at the same time.

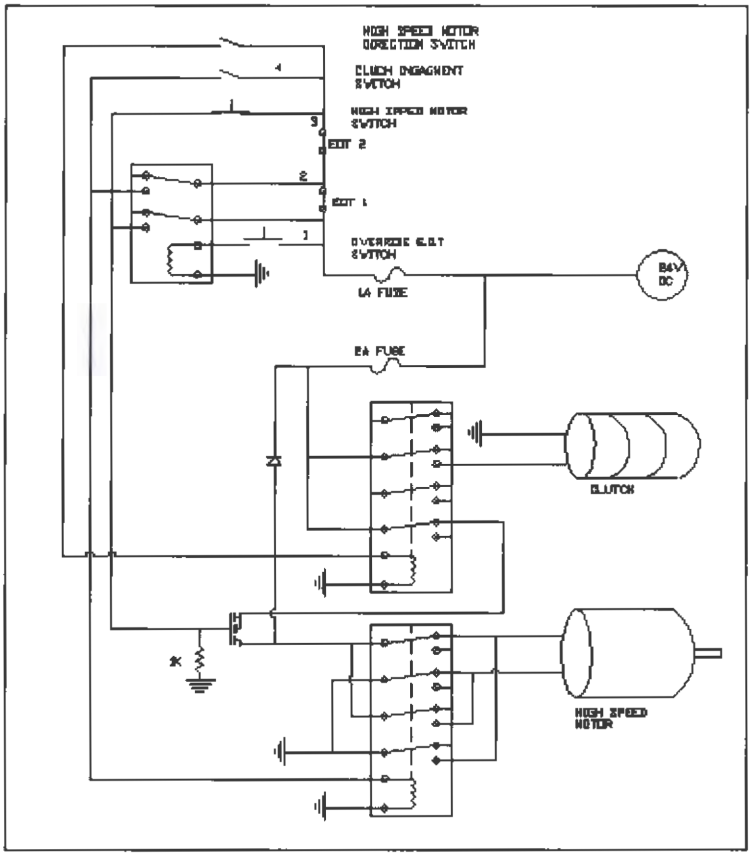

Figure 29 Control Circuit for Linear Translator

3.7 Furnace Stands

The furnace stand is designed to hold the furnace, linear translator and motor driver firmly while transmitting no vibration to the growth ampoule. The furnace is held at a comfortable working height and allows full access to all components for ease of operation. The stand and its sub-components are also adjustable to allow for the addition of such things as cooling tail on the ampoule and acoustic wave mixing which may be added for later experiments. Figure 30 illustrates the design of the stand and the position of the mounting surfaces for the translator and motor driver. The motor mount is vibration isolated for the base, which can be leveled by using four adjustable feet (not shown).

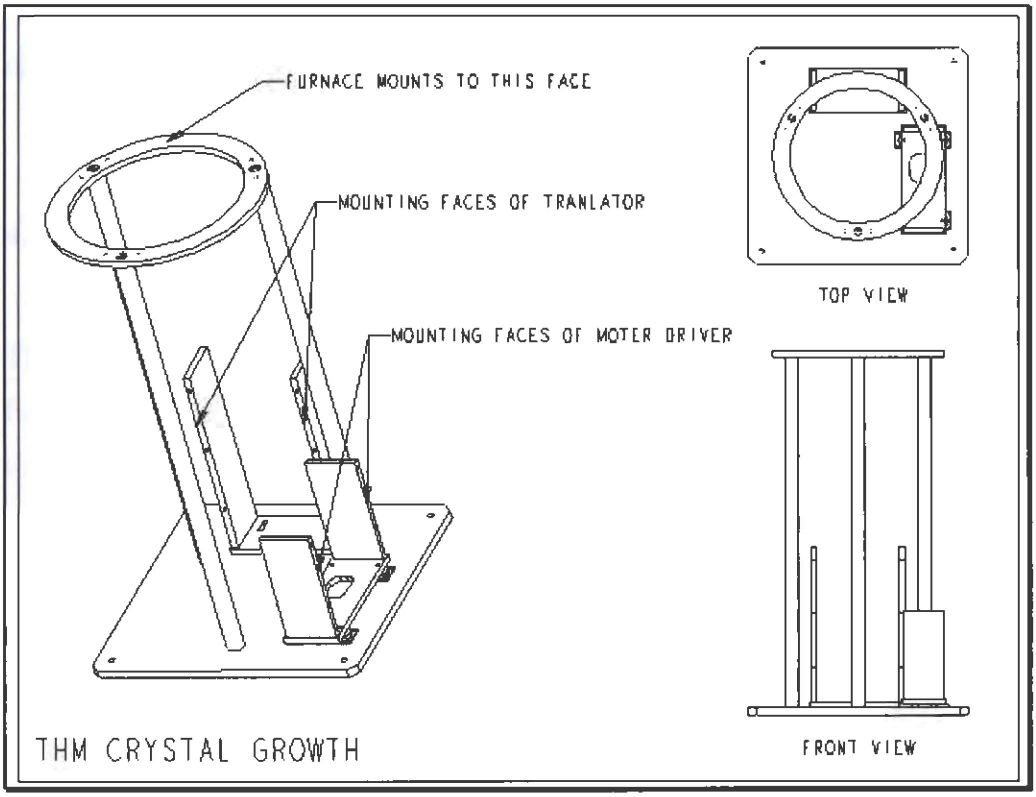

Figure 30 Furnace Stand with Mounts for Motor Diver and Translator

4 Operating Procedure

4.1 *Introduction*

The purpose of this chapter is to give all future operators the knowledge, specific to this furnace, which they will need to successfully grow crystals. This chapter is not intended to give all the specifics on how to grow crystals by the THM, method and a strong knowledge of the THM crystal growth technique will be needed to successfully use the equipment described in this chapter. This chapter will describe the adjustment, replacement and maintenance of all parts requiring such procedures as well as the operation of all the components in the design.

4.2 *Furnace Assembly*

The furnace base cooling block and shell can be assembled and mounted on the stand prior to the installation of all interior components. The solenoids can now be installed and bolted to the bottom plate of the furnace. Care must be taken to mark the solenoid leads so that the orientation of the field they generate will be known once the top plate is in place and the solenoids cannot be seen. This can be done by marking all the leads that come from the inside of the solenoids. Now the furnace liner, bottom and middle marinite rings, and heater can be positioned. The heater leads should run to the cold side of the insulation where they attach to the high temperature wire by means of two copper couplings. This wire runs to a plug, which will be fixed to the top plate. Caution should be taken to ensure that the solenoids are protected from contacting the coupling by the sheets of mica. In order to align the remaining components two 1/8-inch steel rods can now be positioned in the two holes in the surface of the heater. Now the top marinite ring and the fire brick can be put into position, the two steel rods assure the alignment of the insulation so that the thermocouples can later be positioned into the furnace. In order to facilitate the positioning of all the wiring to the top plate three sections of 10-32 threaded rod should be screwed into the top surface of the furnace shell. The top plate can then rest on nuts that are near the top of such rods and hold the top plate between 1-1/2 and 2 inches above the furnace shell. Once all twelve solenoid wires, the heater, and ground wire are connected, the three threaded rods can be removed and the top plate bolted into place. The plug for the heater can then be bolted into place. The marinite alignment cap should now be fixed on top of the top plate with the three alignment blocks. This cap should be positioned so that the furnace liner is concentric with the cooling block and the ampoule will slide smoothly through the furnace. The two steel rods can now be removed and thermocouples positioned in the holes down the sides of the furnace liner

4.3 Furnace Operation

The furnace is controlled with the Omega CN3240 temperature controller. Prior to using the controller, the constants that control the PID algorithm must be set. This can be done automatically with the auto tuning function which is outlined in the operator's manual. In order to achieve the most stable operation the tuning function should be run while under as close to normal operating conditions as possible. This includes having the cooling water running. The controller can now be set to ramp up to and hold the desired growth temperature.

The cooling system has two basic components, a chiller and a pump. These are used to circulate cooling water through copper piping that is wrapped around the outside of the cooling block. The copper pipe should be held in place with the stainless steel sleeve to help ensure good thermal contact. Thermal paste can also be used to decrease the thermal resistance between the cooling block and the copper coil. The pump can be operated independently of the chiller, it has an on off switch and speed controller. The chiller ensures uniform cooling is supplied to the cooling block by holding the cooling fluid at a constant temperature and needs only to be turned on and an appropriate temperature set.

Figure 31 Controller for Linear Translator

4.4 Linear Translator Operation

The linear translator has two control units. The first controls the high speed motor and clutch and it is also connected to the end of travel switches, which disable the high-speed motor and disengage the clutch when open. This control box has a direction selector and a push button switch that operates the high-speed motor, see Figure 31. A rocker switch selects either the clutch or the high-speed motor. The non-selected item will be inoperable while the other is in engaged. There is also an override switch that enables the operator to move the carriage if an end of travel switch has been engaged. In order to perform a growth run the operator should first select the high speed motor, then use the direction switch and high speed motor push button to position the ampoule at the desired location. The clutch can now be selected, deselecting the high-speed motor. Once the ampoule is ready to be moved the control unit for the low speed motor should be engaged. If the fixed speed AC clock motor is being used this is done by a control switch on the control box of that motor. If the stepper motor is being used a program must be written in the IDC Application Developer software and downloaded to the S6961

Micosteping smart drive. This program requires only a few lines of code defining the required speed, acceleration and time or travel distance.

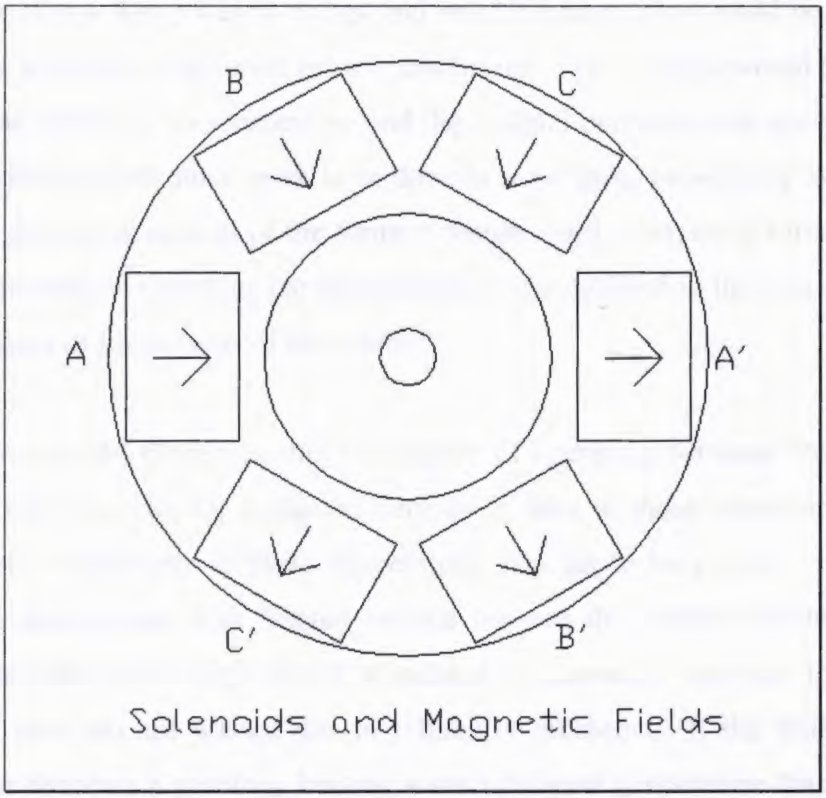

Figure 32 Magnets Position and Field Orientation

4.5 Rotating Magnetic Field Operation

It is important to ensure that the solenoids are correctly connected to their power supply since it is difficult to measure the magnetic field strength, and incorrect connection may not be detected. All six solenoids are wound in the same direction and installed symmetrically around the axial center of the furnace. The solenoids are connected in sets of two, each set are in parallel with each other and on opposite sides of the furnace. Since all the solenoids are symmetric, one solenoid out of each set of two must be wired with the reverse polarity of its twin, see Figure 32. In the figure the prime (') indicates the opposite polarity of the same unit. The controller powers the solenoids in the order A,B,C,-A,-B,-C. Which solenoid is chosen as "A" is inconsequential as long as the sequence is maintained.

5 Conclusion and Future Recommendations

The objective of this thesis was to design and build a furnace that would be able to grow crystals under a variety of different growth conditions. The furnace would be capable of performing the necessary experiment to find the optimal parameters to grow CdZnTe by THM. Since there is still much work to be done to see if these parameters can be found it is difficult to assess the success of the furnace design. Still, comparing furnace operating ranges with the desired operating parameters that where outlined in the first chapter gives a good indication of the success of the design.

It was desired that the furnace would be capable of operating between 750 and 950°C. The furnace has been run for sustained periods of time at these temperatures with no adverse effects. Reliability at these temperatures has yet to be proven. However, the only furnace components with limited service life are the heater and thermocouples. These components can be replaced at scheduled maintenance intervals to ensure that experimental runs are not wasted due to reliability problems. If the reliability of the furnace heater becomes a problem, heating wires of higher temperature than the Kanthal A1 are available. These include Kanthal APM, Kanthal 1700 and Kanthal 1800. Even though 950 °C is well within the Kenthal A1's 1200°C operating range higher temperature wire may withstand the thermal cycling that lower temperature wires cannot.

Initial studies suggest that the temperature profile of the new furnace will produce a higher growth rate due to its increased temperature gradient. THM-1 design has temperature gradient over 250 °C/cm, almost twice that of Amistar designs with 160 °C/cm (See Figure 20). The final test for the success of the furnace temperature profile will be actual crystal growth, since it is not clear what the optimum temperature gradient is. The furnace design addresses this point by making the temperature gradient partly controllable by varying the cooling fluid flow and temperature as well as the furnace set point. Further adaptation can be achieved by altering the height of the cooling fin on the cooling block as well as incorporating different heater designs. Radiation is the major means of heat transfer at temperatures the heater is operated at (between 850 and 950°C). A heater design that focuses the radiant heat in a narrow band along the ampoule wall could produce a narrower higher temperature zone and higher temperature gradients.

The linear translator effectively moves the ampoule at speeds ranging from above the desired 10 mm/day to below the 1mm/day. For added operating convenience a second higher speed motor was also included in the design making it possible to quickly position the carriage in the desired position. The stepper motor is simple to operate and it adjusts to precise speeds. Since there is no known case of THM equipment being run with stepper motors the translator was made so that other motor types could also be used, in case the stepping action of the motor caused too much vibration. The gearing on the motor was made to minimize such vibration, and it is felt that it will not be a problem. The translator is designed to lower the ampoule from the bottom. This allows the application of acoustic wave emitting devices to be attached to the bottom of the ampoule as well as different cooling apparatus.

The field generated by the six solenoids was measured individually and ranged in value between 1.3 and 1.4 mT at a distance of about 3.5 inches from the face of the solenoid with a 12.5V power supply. With the solenoids operating in pairs so that their field strength is added this gives a total field of about 2.7 mT. It is incorrect to assume that the full field will be generated by the solenoids operating at higher frequencies since inductance will reduce the current in each coil. By observing the voltage across each solenoid with an oscilloscope while the magnets ran at different frequencies, the spike resulting from the inductance of the solenoids was observed to occupy approximately 50% of the one time in each cycle at 150Hz. This means that at 150Hz 50% of the time on each solenoid is used to overcome impedance and arrive at full current. At higher frequency this amount increases. For this reason it was felt that 150Hz should be a maximum operating frequency of the magnets. If a method of measuring the field at higher frequencies could be found it would be possible to assess the magnets effect more accurately. This may allow higher frequencies to be used. Higher frequencies could also be achieved by increasing the voltage to the magnets or double winding them.

The furnace was designed so that future experiments could be performed within a 1.0T static magnetic field. In order to achieve this the furnace diameter was kept as small as possible and no hookups are protruding from the side of the furnace. Since the fixed magnet will operate at cryogenic temperatures it is important that the furnace wall temperatures not be to hot, leading to to much execs excessive work by the cryogenic refrigeration unit. The solenoids and furnace were run for extended periods while warped in a layer of insulation to simulate the reduced convection that will result from the fixed magnet. After over six hours of operation the furnace shell was below 40°C in call cases. At the time of publication the design and construction of a superconducting 1.0 T magnet under way. The inside bore of the magnet is 13.2in. allowing 1/4 of an inch clearance. The furnace was also made with non-magnetic material. Prior to operation with the 1.0T magnet is the furnace should be converted to DC operation. This can be done with the existing controller by simply switching the power to the solid state relay from a 110V 60Hz to a rectified 110V DC power supply.

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APENDIX A Source Code for Ansys Models

```
!----------------------------------------------------------------------------------------------------------
!
!ANSYS command file for 2D Thermal Analysis of Amistar THM Design
!
FINISH                                  !End and Clear all Existing Models
/CLEAR.NOSTART
!
/title, THM Amistar Prototype Furnace
!----------------------------------------------------------------------------------------------------------
/UNITS,si                                        !Setting SI Units
/PREP7
!
!                                       !Defining Areas
!
RECTNG,-.002,0,.064,-.064                        !Furnace Liner 2,10
RECTNG,0,.056,.038,.064                          !Top Insulation 4,9
RECTNG,.020,.056,.012,.038                       !Middle Insulation 4,9
RECTNG,0,.056,0,.012                             !Bottom Insulation 4,9
RECTNG,0,.056,0,-.010                            !Bass Plate 3,7
RECTNG,0,.034,-.010,-.064                        !Cooling Block 3,7
!
!
!                                       Properties of material 2 (quatrs liner)
!
UIMP,2,DENS, , ,2700,                            !Density
UIMP,2,KXX, , ,0.78,                             !Thermal Conductivity
UIMP,2,C, , ,.84,                                !Specific Heat
UIMP,2,HF, , ,00,                                !Convective Film Coefficient
!
!
!                                       Properties of material 5 (cooling block "Al")
!
UIMP,5,DENS, , ,2787,                            !Density
UIMP,5,KXX, , ,164,                              !Thermal Conductivity
UIMP,5,C, , ,.883,                               !Specific Heat
UIMP,5,HF, , ,00,                                !Convective Film Coefficient
!
!                                       Properties of material 3 (fire brick, "Insalcor")
!
MPTEMP,1,300,533.15,810.97,1088.71,1366.48,1644.26
!
MPDARA,KXX,3,1,0.8,0.8955,0.9118,1.0258,1.2375,1.498,
!
UIMP,3,DENS, , ,2707,                            !Density
UIMP,3,C, , ,.896,                               !Specific Heat
UIMP,3,HF, , ,2.64,                              !Convective Film Coefficient
!
!                                       Selecting Element Type
ET,2,PLANE77
ET,1,PLANE55
!
AGLUE,1,2,3,4,5,6                       !Gluing Areas
!
ESIZE,0.002,0,                          Setting Mesh Size
!
!                                       Setting Material Properties and Meshing
```

```
ASEL, , , ,12                              !Selecting Liner
AATT,2, ,2,0                               !Setting, mat.#, ,eliment#.,COORDINATE#
Amesh,all                                  !Meshing volume
Asel,all                                   !Unslecting!
!
ASEL, , , ,8                               !Selecting Cooling Block
ASEL,A, , ,11
AATT,5, ,2,0                               !Setting, mat.#, ,eliment#.,COORDINATE#
Amesh,all                                  !Meshing volume
Asel,all                                   !Unslecting!
!
ASEL, , , ,9                               !Selecting Insulation
ASEL,A, , ,10
ASEL,A, , ,7
AATT,3, ,2,0                               !Setting, mat.#, ,eliment#.,COORDINATE#
Amesh,all                                  !Meshing volume
Asel,all                                   !Unslecting!
!
/SOLU
!
NSUBST,2,5,2
AUTOTS,ON
!
DL,38, ,TEMP,1170,1               !Fixing temp. Around Heater
DL,32, ,TEMP,1170,1
DL,33, ,TEMP,1170,1
DL,12, ,TEMP,1170,1
!
DL,22, ,TEMP,303,1                !Fixing temp. on outside of Cooling Block
!
SOLVE                             Solving Model
!
FINISH
!
! !----------------------------------------------------------------------------------------------------------------
!
/POST1                            Showing Results
SET,LAST
PLNSOL,TEMP, ,0,
!


!----------------------------------------------------------------------------------------------------------------

FINISH                            !End and Clear all Existing Models
/CLEAR.NOSTART
!
!ANSYS Command File for 2D Thermal Analysis of THM Furnace (with Sloping cooling block)
!
/title, THM Sloping Cooling Block Design
!
/UNITS,si                    !SI Units
!----------------------------------------------------------------------------------------------------------------
!
/PREP7
```

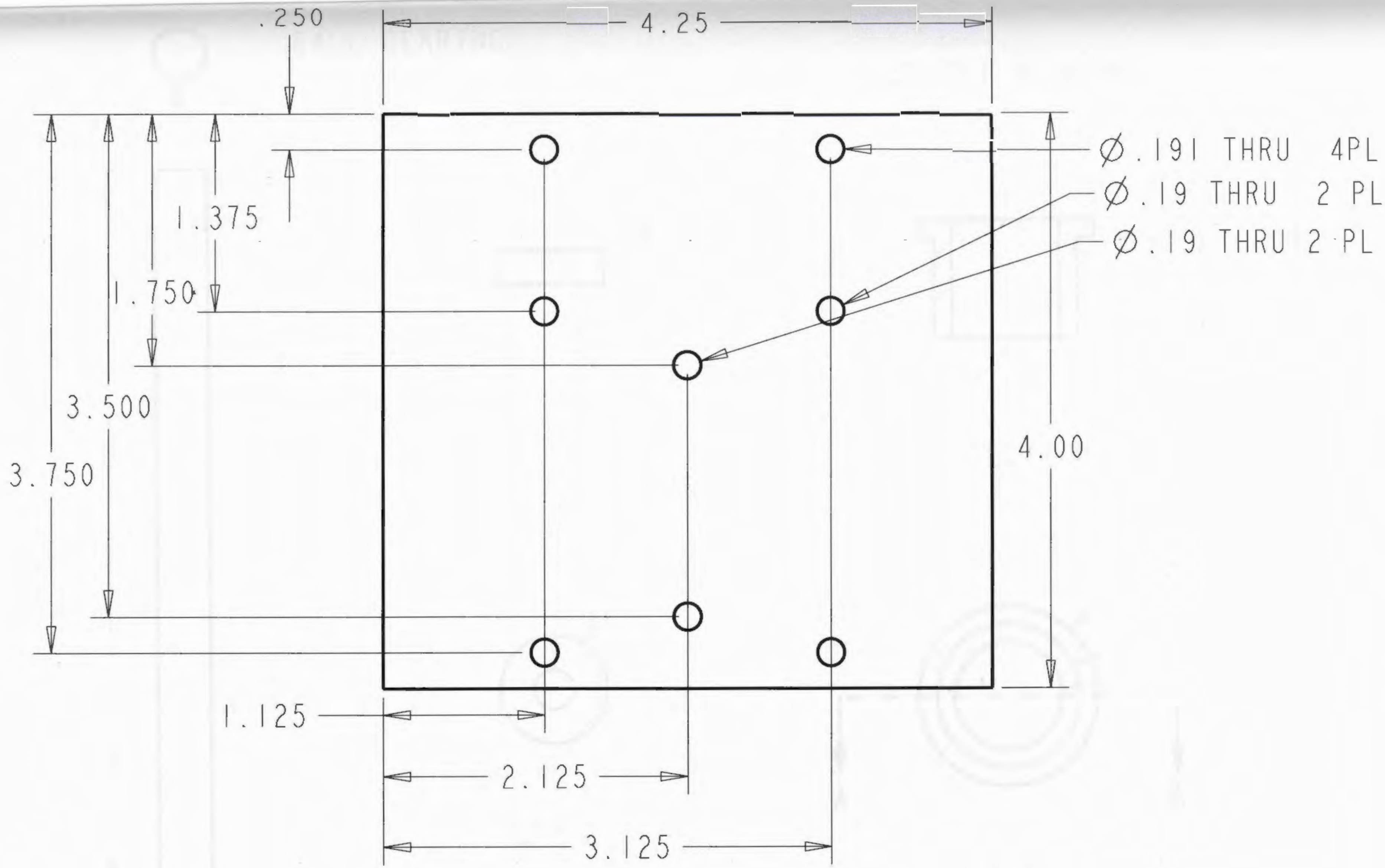
```
!
!                                        Defining Areas
!
RECTNG,0,.0020,0,.048                   !Furnace Liner 2,10
RECTNG,.002,.058,.024,.048              !Top Insulation 4,9
RECTNG,.020,.058,0,.024                 !Middle Insulation 4,9
RECTNG,.024,.058,0,-.024                !Bottom Insulation 4,9
LSTR,1,16                               !lines for insulation
LSTR,1,13                               !lines for insulation
AL,16,18,17                             Make Areas with Lines
RECTNG,0,.036,-.034,-.06                !Cooling Block 3,7!
LSTR,13,19                              !lines for insulation
LSTR,1,20                               !lines for insulation
AL,24,18,23,21                          Make Areas with Lines
!
!                                        Properties of material 2 (quatrs liner)
!
UIMP,2,DENS, , ,2700,                   !Density
UIMP,2,KXX, , ,0.78,                    !Thermal Conductivity
UIMP,2,C, , ,.84,                       !Specific Heat
UIMP,2,HF, , ,00,                       !Convective Film Coefficient
!
!
!                                        Properties of material 5 (cooling block "Al")
!
UIMP,5,DENS, , ,2787,                   !Density
UIMP,5,KXX, , ,164,                     !Thermal Conductivity
UIMP,5,C, , ,.883,                      !Specific Heat
UIMP,5,HF, , ,00,                       !Convective Film Coefficient
!
!                                        Properties of material 3 (fire brick, "Insalcor")
!
MPTEMP,1,300,533.15,810.97,1088.71,1366.48,1644.26
!
MPDARA,KXX,3,1,0.8,0.8955,0.9118,1.0258,1.2375,1.498,
!
UIMP,3,DENS, , ,2707,                   !Density
UIMP,3,C, , ,.896,                      !Specific Heat
UIMP,3,HF, , ,2.64,                     !Convective Film Coefficient
!
!                                        !Selecting Element Type
ET,1,PLANE55
ET,2,PLANE77
!
AGLUE,1,2,3,4,5,6,7                      Gluing Areas
!
ESIZE,0.002,0,                           Setting Mesh Size
!
!                                        Matching material Properties and Areas and Meshing
!
ASEL, , , ,9                            !Selecting Liner
AATT,2, ,2,0                            !Setting, mat.#, ,eliment#., Coordinate#
AMESH,all                               !Meshing volume
ASEL,all                                !Unslecting!
!
ASEL, , , ,7                            !Selecting Cooling Block Triangle
```

```
AATT,5, ,2,0                !Setting, mat.#, ,eliment#., Coordinate #
Amesh,all                   !Meshing volume
Asel,all                    !Unslecting!
!
ASEL, , , ,10               !Selecting triangle part of insulation
AATT,3, ,2,0                !Setting, mat.#, ,eliment#., Coordinate #
Amesh,all                   !Meshing volume
Asel,all                    !Unslecting!
!

!
ASEL, , , ,11               !Selecting Insulation
ASEL,A, , ,12
ASEL,A, , ,8
AATT,3, ,2,0                !Setting, mat.#, ,eliment#.,COORDINATE#
Amesh,all                   !Meshing volume
Asel,all                    !Unslecting!
!
MSHKEY,1                    Use mapped meshing
ASEL, , , ,6                !Selecting Cooling Block
AATT,5, ,2,0                !Setting, mat.#, ,eliment#.,COORDINATE#
Amesh,all                   !Meshing volume
Asel,all                    !Unslecting!
!
!--------------------------------------------------------------------------------------------------------------
!
/SOLU
!
DL,27, ,TEMP,1170,1         !Fixing temp. Around Heater
DL,32, ,TEMP,1170,1
DL,29, ,TEMP,1170,1
DL,12, ,TEMP,1170,1
!
DL,20, ,TEMP,303,1          !Fixing temp. on outside of Cooling Block
!
!
SOLVE                       ! Solve Model
!
FINISH
!
! !--------------------------------------------------------------------------------------------------------------
!
/POST1                      Display Results!
SET,LAST
PLNSOL,TEMP, ,0,



!--------------------------------------------------------------------------------------------------------------
!
ANSYS Command File for 2D Thermal Analysis of THM-1Furnace (extended cooling block)
!
!
/title, THM Extended Cooling Block Design
!
```

```
/UNITS,si                          !SI Units
!
!----------------------------------------------------------------------------------------------------------------
!
/PREP7
!
!                                  Defining Areas
!
RECTNG,0,.002,0,.050                     !Furnace Liner 2,10
RECTNG,.002,.010,0,.002                  !Insulation Small Block4,9
RECTNG,.010,.058,-.022,.002              !Bottom Insulation 4,9
RECTNG,.022,.058,.002,.026               !Middle Insulation 4,9
RECTNG,.002,.058,.026,.050               !Top Insulation 4,9

RECTNG,0,.002,0,-.008                    !Cooling Block top very small
RECTNG,0,.010,-.008,-.022                !Cooling Block middle small
RECTNG,0,.058,-.022,-.032                !Bottom Plate -long
RECTNG,0,.036,-.032,-.060                !Cooling Block big bottom
!
AGLUE,1,2,3,4,5,6,7,8,9                  !Glue Areas
LSTR,22,27                               !lines for insulation
LSTR,2,27                                !lines for insulation
LSTR,6,27                                !lines for insulation
AL,2,39,57                               !Make area with lines
AL,38,52,2                               !Make areas with lines

AGLUE,1,2,11,12,13,14,15,17,18     !Gluing Areas
!
!                                  Properties of material 2 (quartz liner)
!
UIMP,2,DENS, , ,2700,                    !Density
UIMP,2,KXX, , ,0.78,                     !Thermal Conductivity
UIMP,2,C, , ,.84,                        !Specific Heat
UIMP,2,HF, , ,00,                        !Convective Film Coefficient
!
!
!                                  Properties of material 5 (cooling block "Al")
!
UIMP,5,DENS, , ,2787,                    !Density
UIMP,5,KXX, , ,164,                      !Thermal Conductivity
UIMP,5,C, , ,.883,                       !Specific Heat
UIMP,5,HF, , ,00,                        !Convective Film Coefficient

!                                  Properties of material 3 (fire brick, "Insalcor")
!
MPTEMP,1,300,533.15,810.97,1088.71,1366.48,1644.26
!
MPDARA,KXX,3,1,0.8,0.8955,0.9118,1.0258,1.2375,1.498,
!
UIMP,3,DENS, , ,2707, ,                  !Density
UIMP,3,C, , ,.896,                       !Specific Heat
UIMP,3,HF, , ,2.64,                      !Convective Film Coefficient
!
!                                  Selecting Element Type
!
ET,3,PLANE55
```

```
ET,2,PLANE77
!
ESIZE,0.001,0,                    Setting Mesh Size
!
ASEL, , , ,16                          !Selecting Liner
AATT,2, ,2,0                           !Setting, mat.#, ,eliment#., Coordinate#
AMESH,all                              !Meshing volume
ASEL,all                               !Unslecting!
!
!
ASEL, , , ,1                           !Selecting Insulation
ASEL,A, , ,11
ASEL,A, , ,12
ASEL,A, , ,14
ASEL,A, , ,18
AATT,3, ,2,0                           !Setting, mat.#, ,eliment#., Coordinate#
Amesh,all                              !Meshing volume
Asel,all                               !Unslecting!
!
ASEL, , , ,2                           !Selecting Cooling Block
ASEL,A, , ,10
ASEL,A, , ,13
ASEL,A, , ,15
ASEL,A, , ,17
AATT,5, ,2,0                           !Setting, mat.#, ,eliment#., Coordinate#
Amesh,all                              !Meshing volume
Asel,all                               !Unslecting!
!
!------------------------------------------------------------------------------------------------------------
!
/SOLU
!
AUTOTS,ON
!
DL,7, ,TEMP,1170,1                !Fixing temp. Around Heater
DL,16, ,TEMP,1170,1
DL,48, ,TEMP,1170,1
DL,53, ,TEMP,1170,1
DL,58, ,TEMP,1170,1
!
DL,34, ,TEMP,303,1                !Fixing temp. on outside of Cooling Block
!
SOLVE                             Solving
!
FINISH
!
! !------------------------------------------------------------------------------------------------------------
!                          Displaying Results
!
/POST1
SET,LAST
PLNSOL,TEMP, ,0,
```

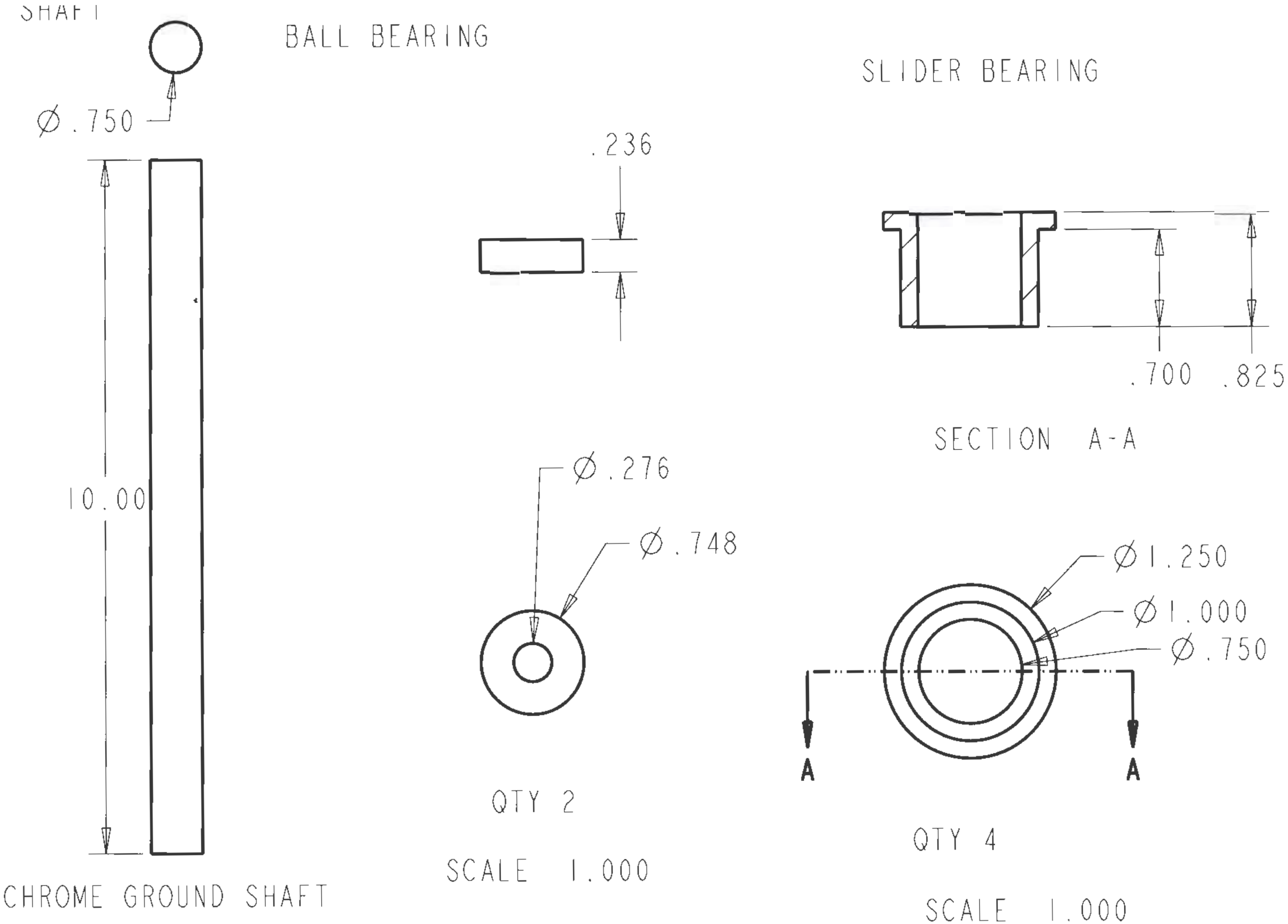
APENDIX B Engineering Drawings



.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

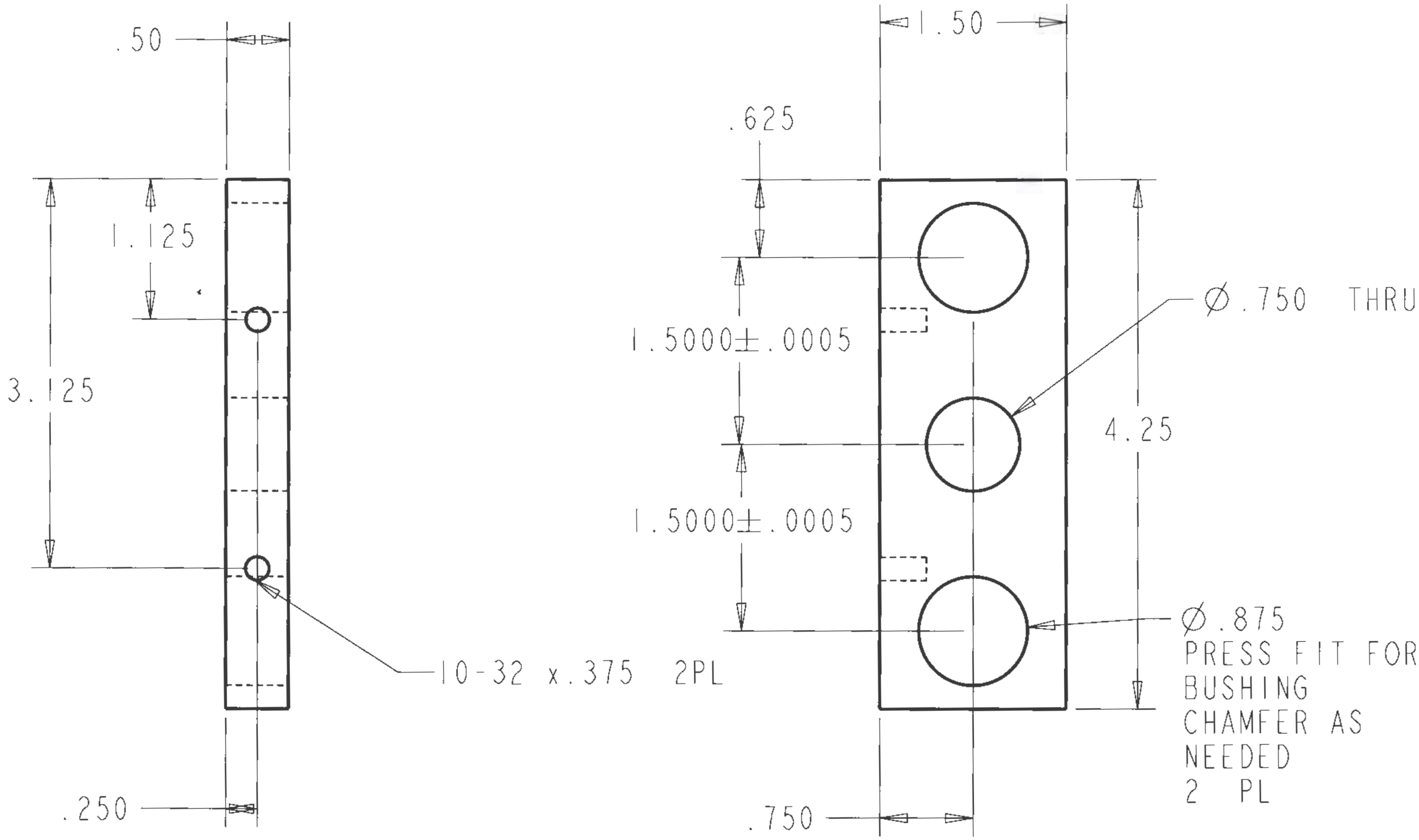
MUST BE MADE FROM PLATE 1/4 in. THICK 1 QTY

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE
	SCALE: 1 REV:
PART UPRIGHT MOVING PLATE	DATE: APRIL 3 /01
MECHANICAL ENGINNERING UVIC	APPROVED BY:



QTY 2
SCALE 0.500

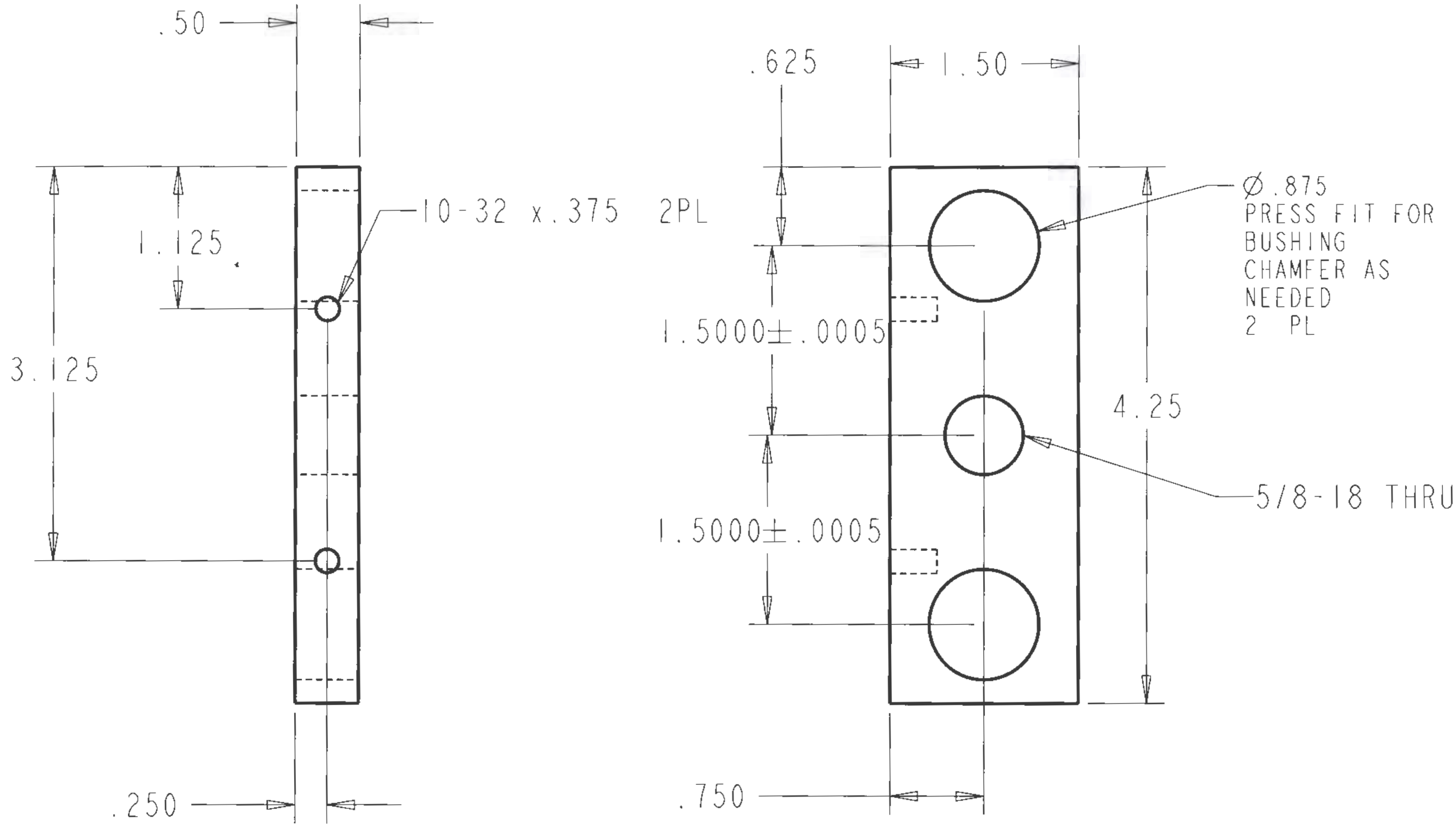
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: SEE NOTES	REV:
PART PARTS	DATE: APRIL 3 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MUST BE MADE FROM PLATE QTY 1

.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

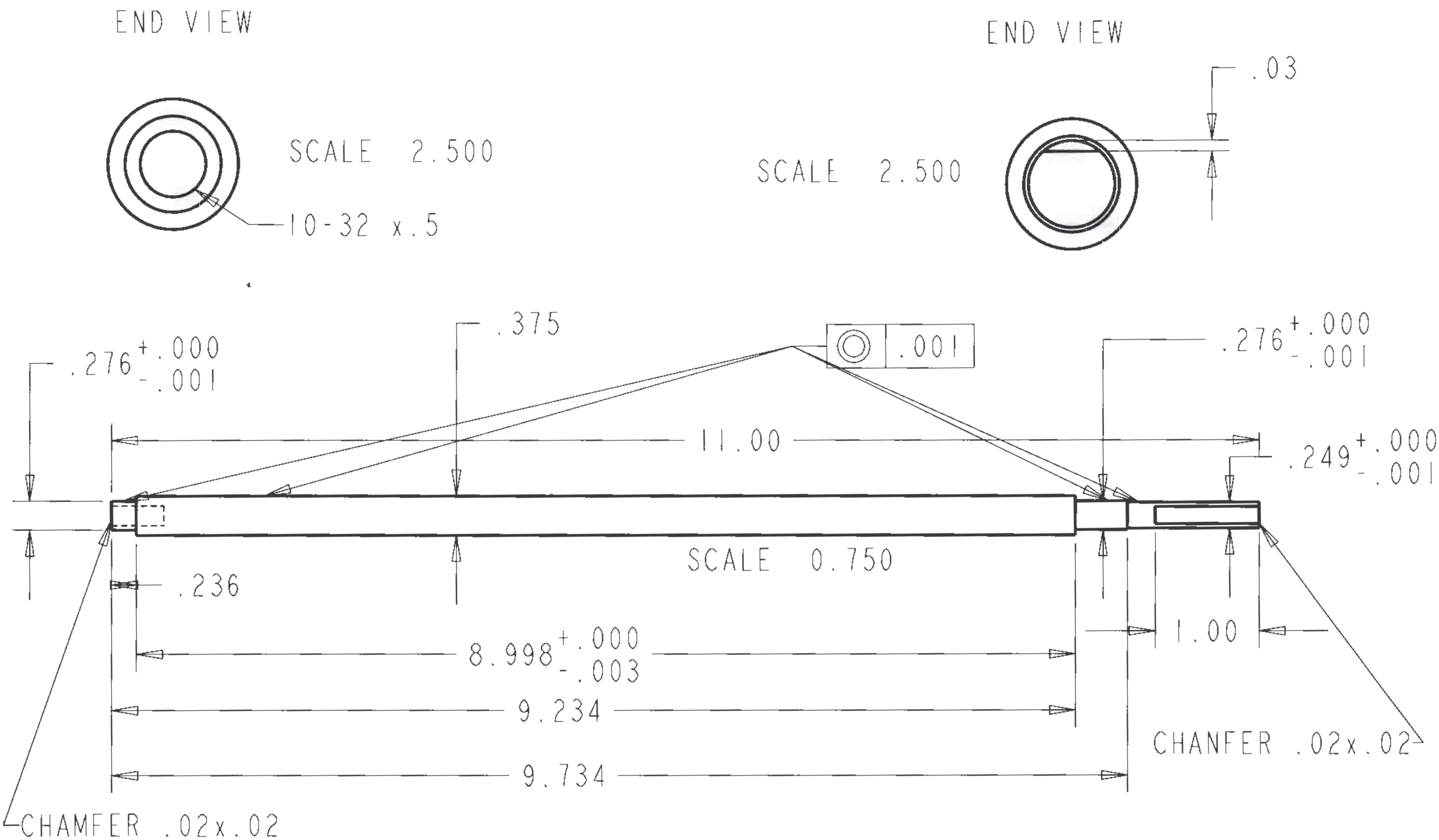
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE
	SCALE: .85 — REV:
PART TOP MOVING PLATE	DATE: APRIL 6 /01
MECHANICAL ENGINNERING UVIC	APPROVED BY:



MUST BE MADE FROM PLATE 1 REQUIRED

.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

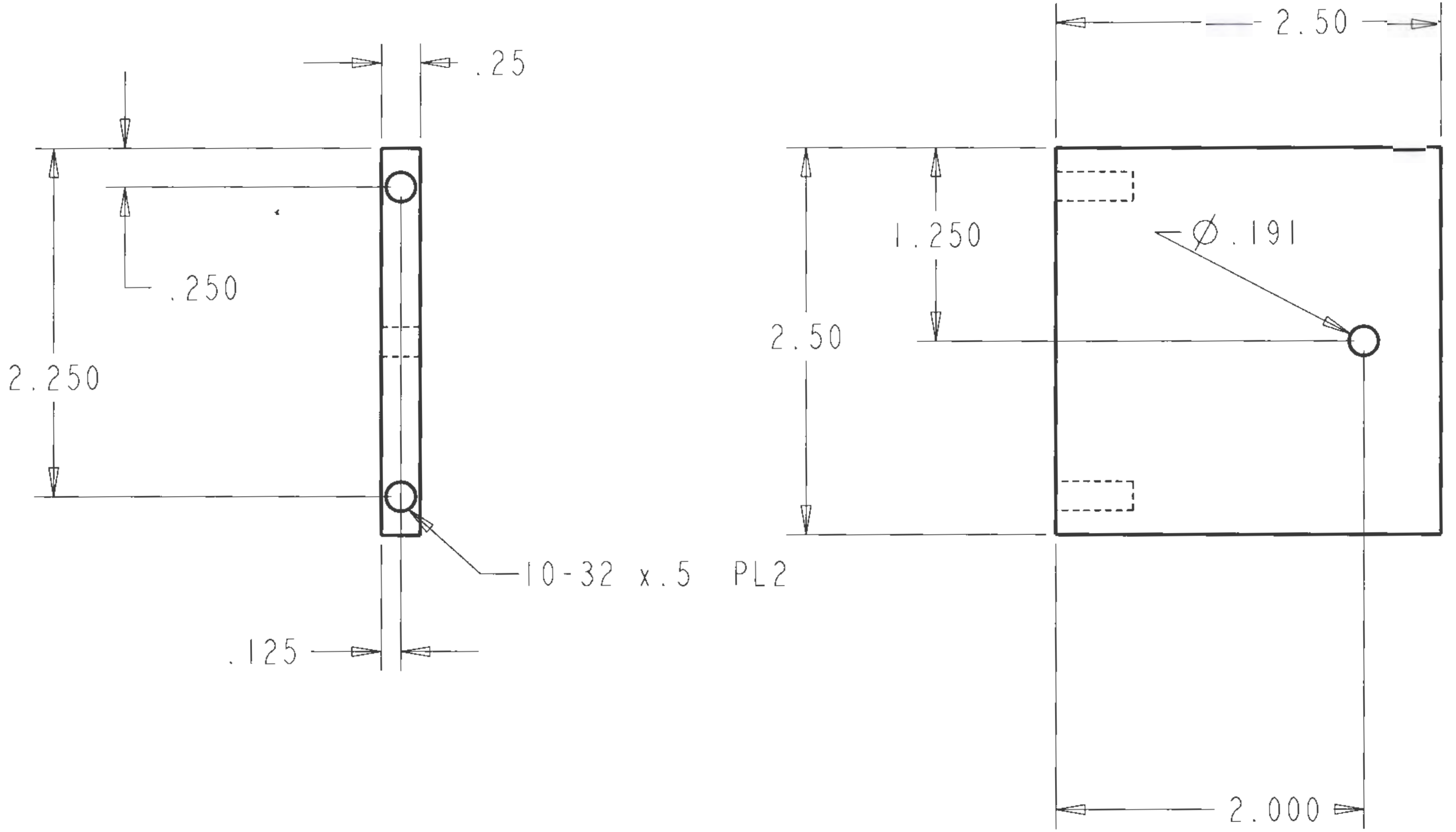
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.85	REV:
PART BOTTOM MOVING PLATE	DATE: APRIL 3 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MADE FROM 3/8-16-1st THREADED ROD

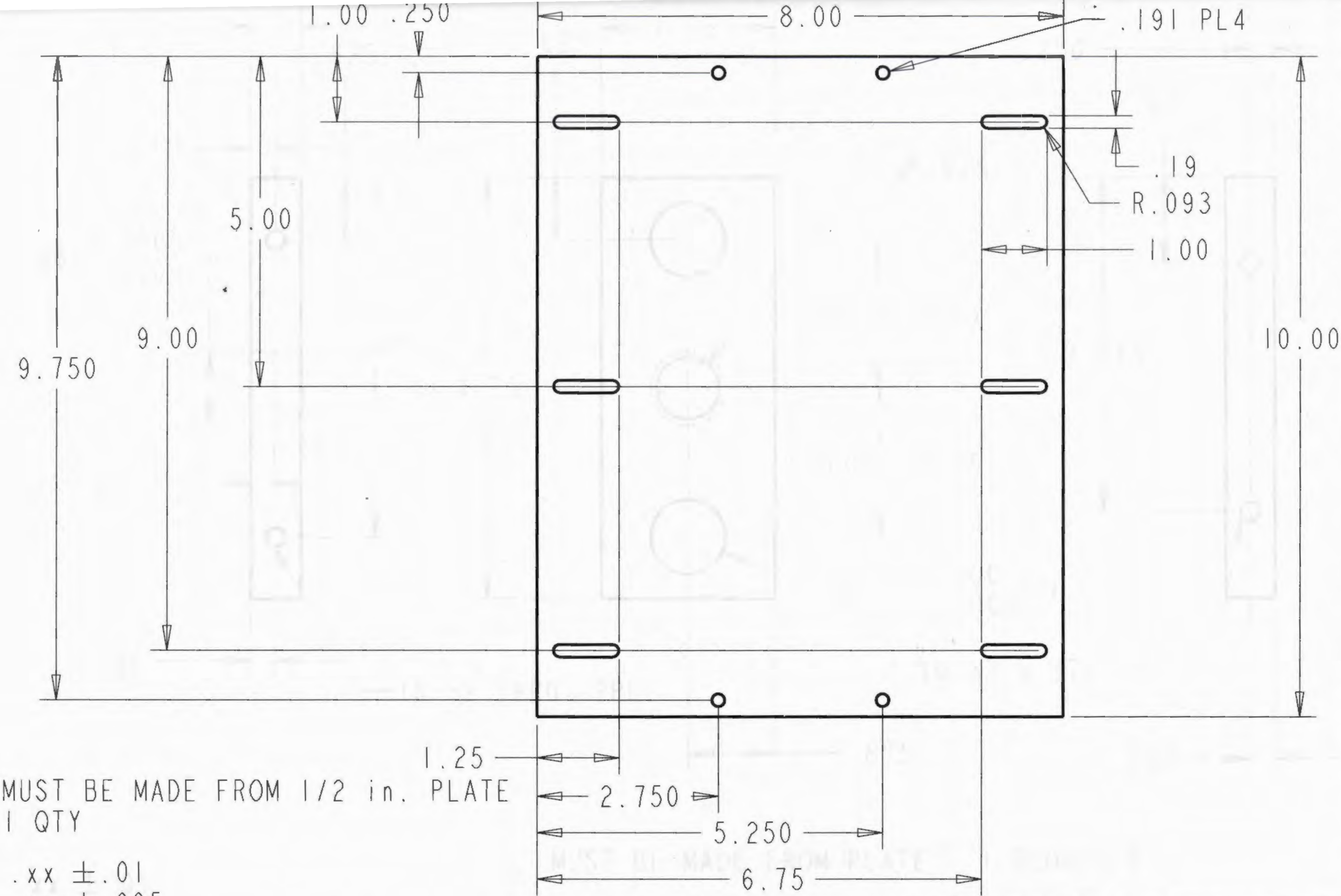
.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE:0.75	REV:
PART LEAD SCREW	DATE: FEB.28 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

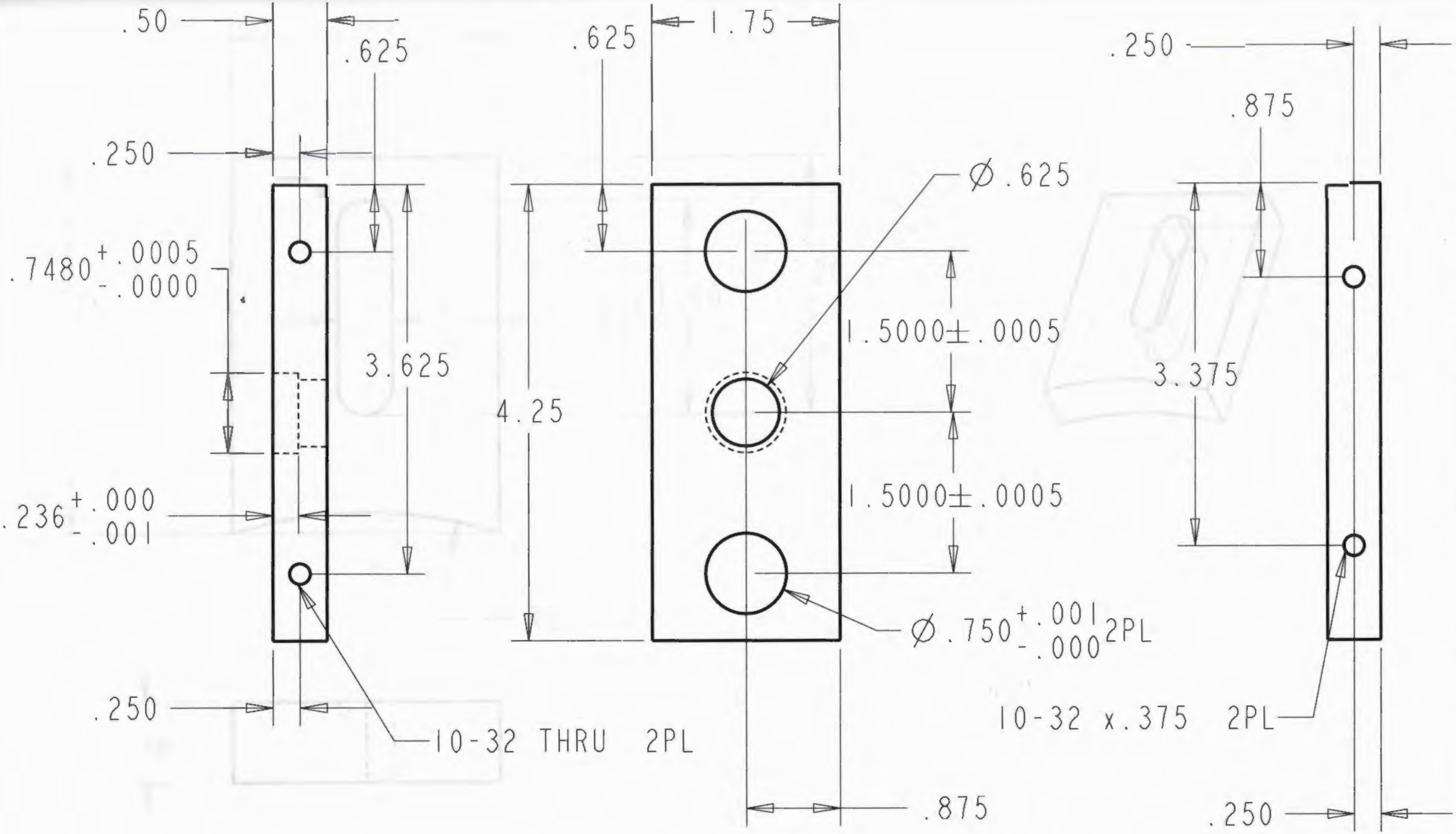
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 1	REV:
PART LIFTING PLATE	DATE: APRIL 3 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MUST BE MADE FROM 1/2 in. PLATE
1 QTY

.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

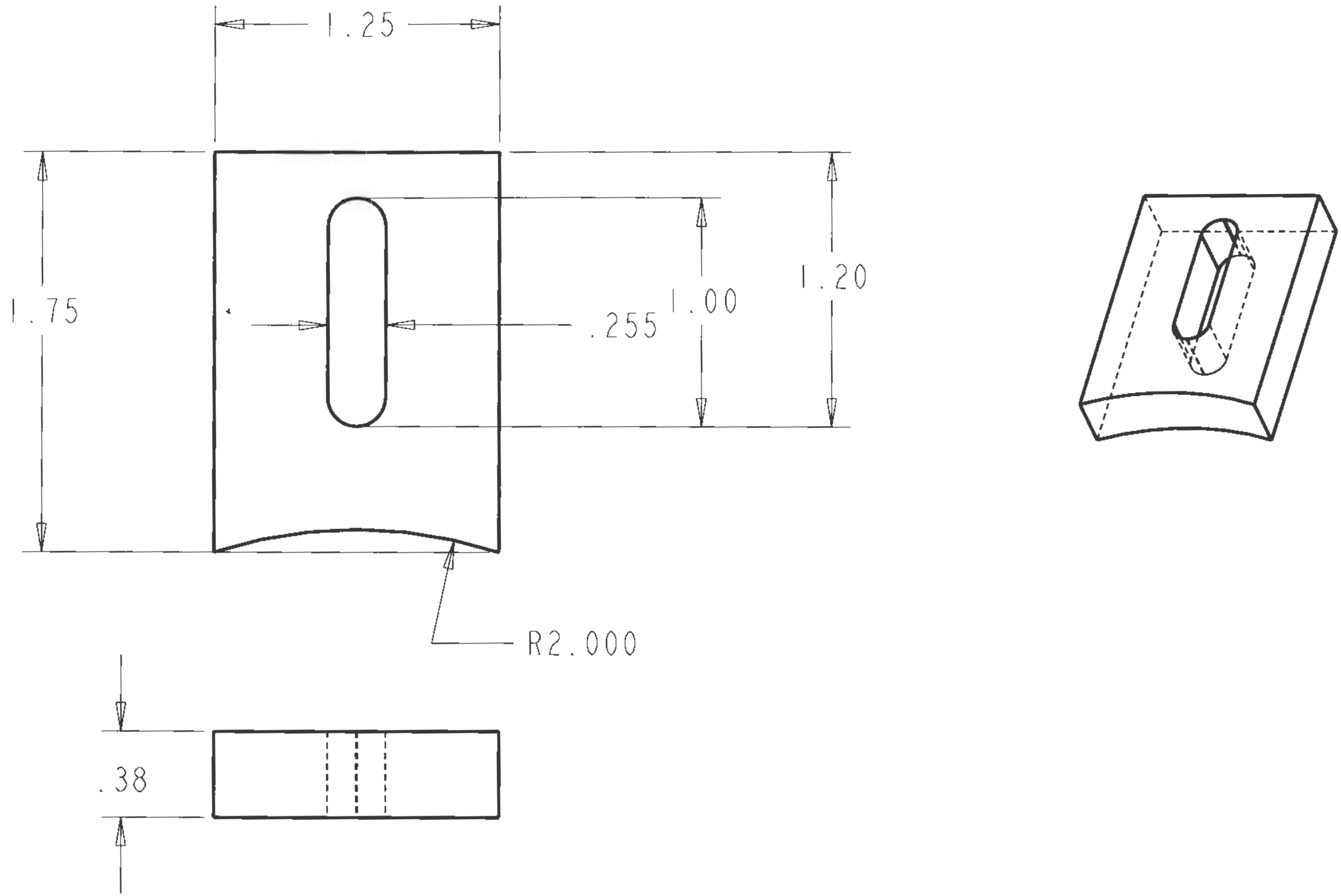
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.5	REV:
PART BACK PLATE	DATE: APLRIL 3 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MUST BE MADE FROM PLATE   1 REQUIRED

.xx ±.01
.xxx±.005
UNLESS OTHERWISE STATED
REMOVE ALL SHARP CORNERS
AND DEBURR

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.75	REV:
PART BOTTOM BEARING MOUNT	DATE: APRIL 4 /01	
MECHANICAL ENGINNERING UVIC	APPROVED BY:	

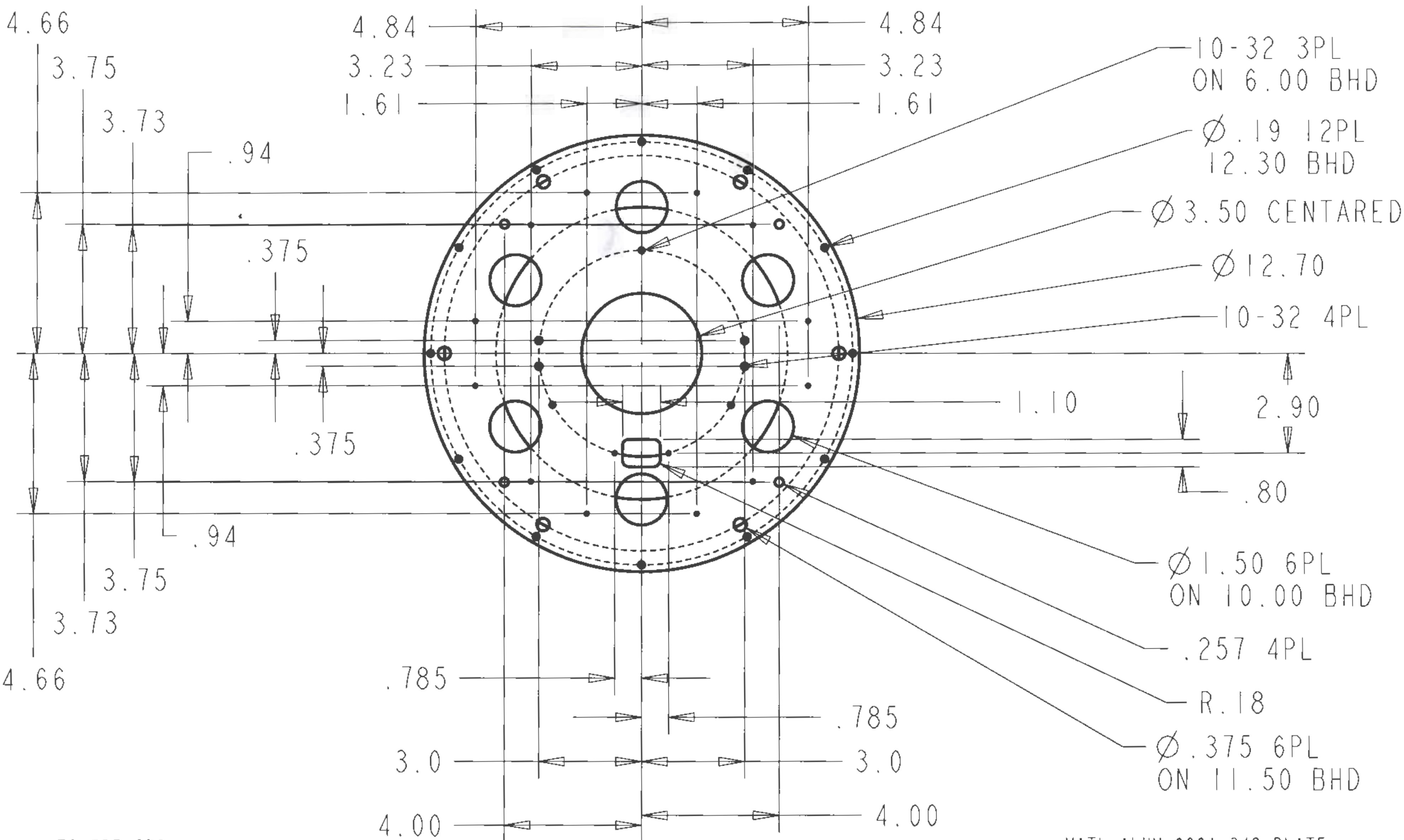


MADE FROM ALUMINUM PLATE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 1.5	REV:
PART TOP BRACE	DATE: MAY 6 /01	QTY: 3
MECHANICAL ENGINNERING UVIC	APPROVED BY:	

TOP PLATE



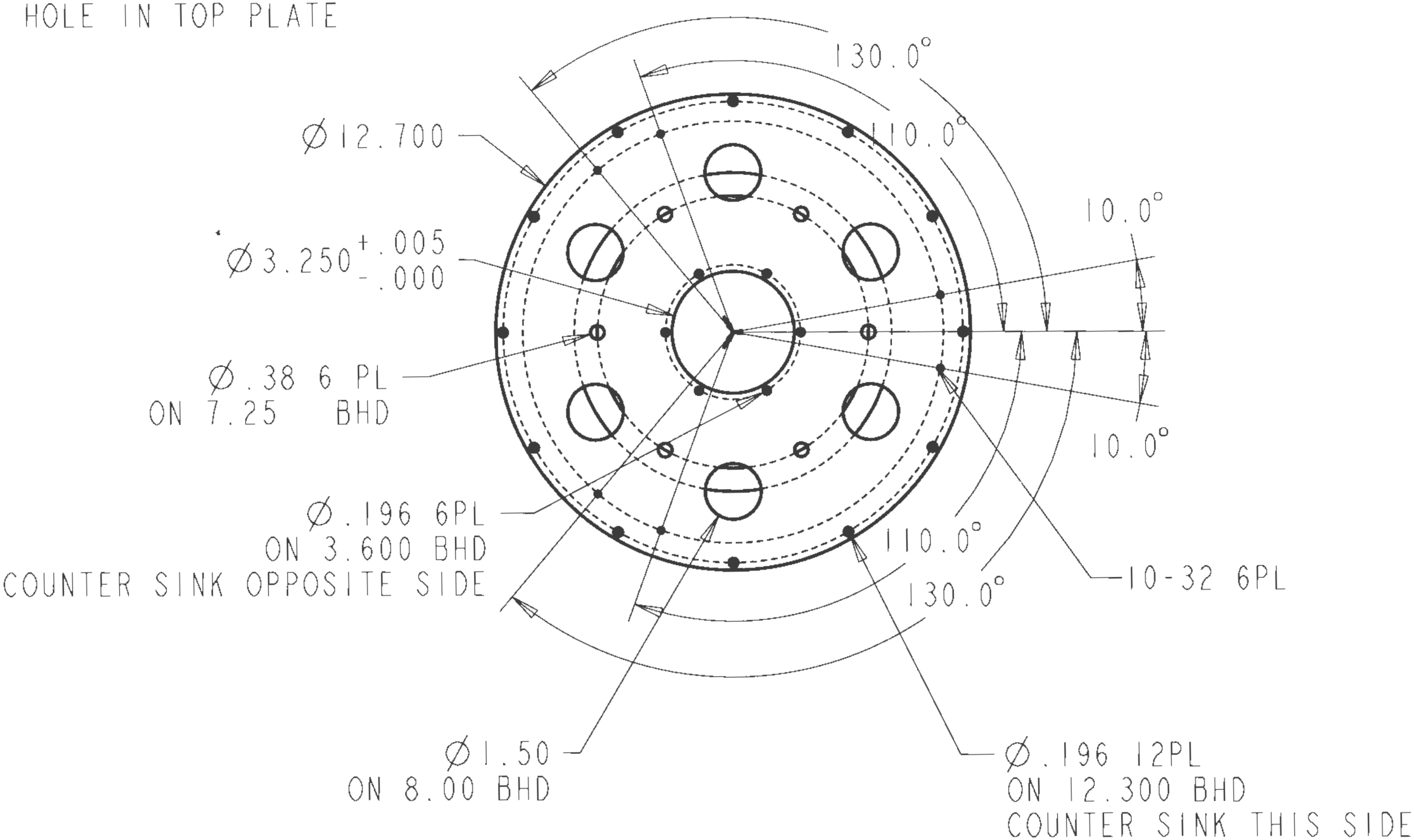
MATL ALUM 6061 3/8 PLATE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.25	REV:
PART TOP PLATE	DATE: MAY 6 /01	QTY: 1
MECHANICAL ENGINNERING UVIC	APPROVED BY:	

CENTER HOLE IN PLATE MUST
BE CONCENTRIC WITH CENTER
HOLE IN TOP PLATE

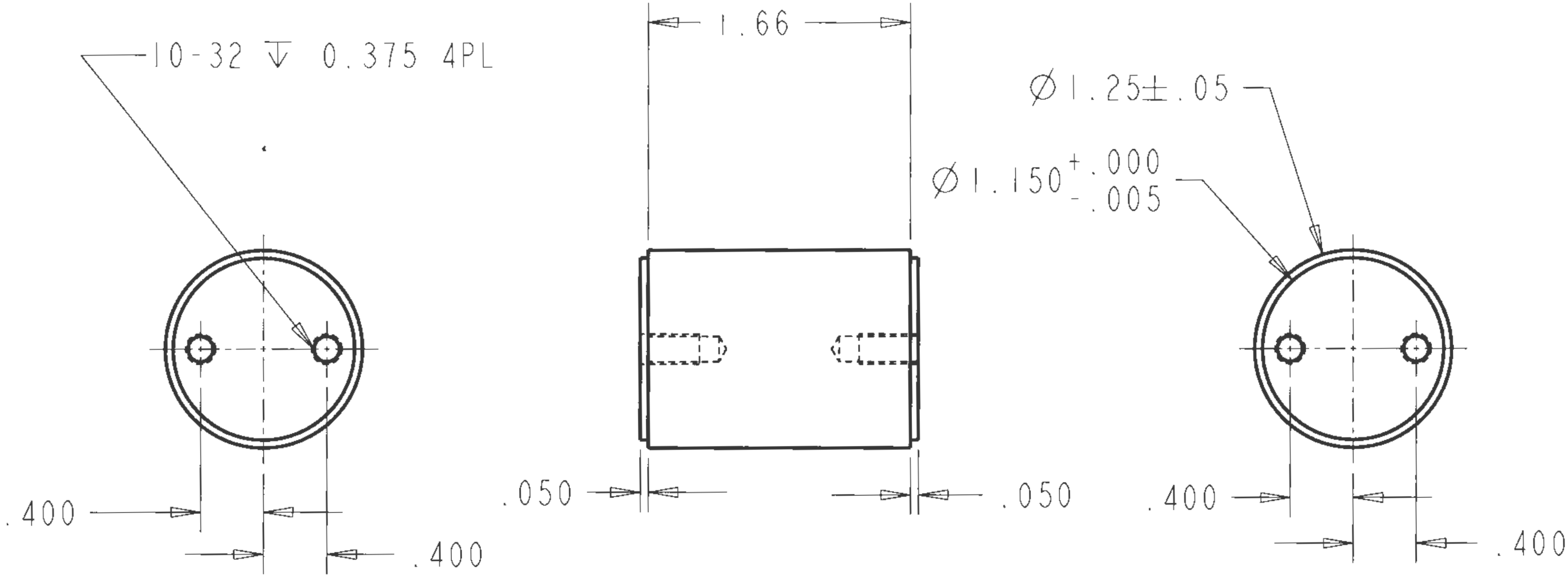
BASE PLATE



MATL ALUM 6061 3/8 PLATE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
ANGLE +/- .1
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

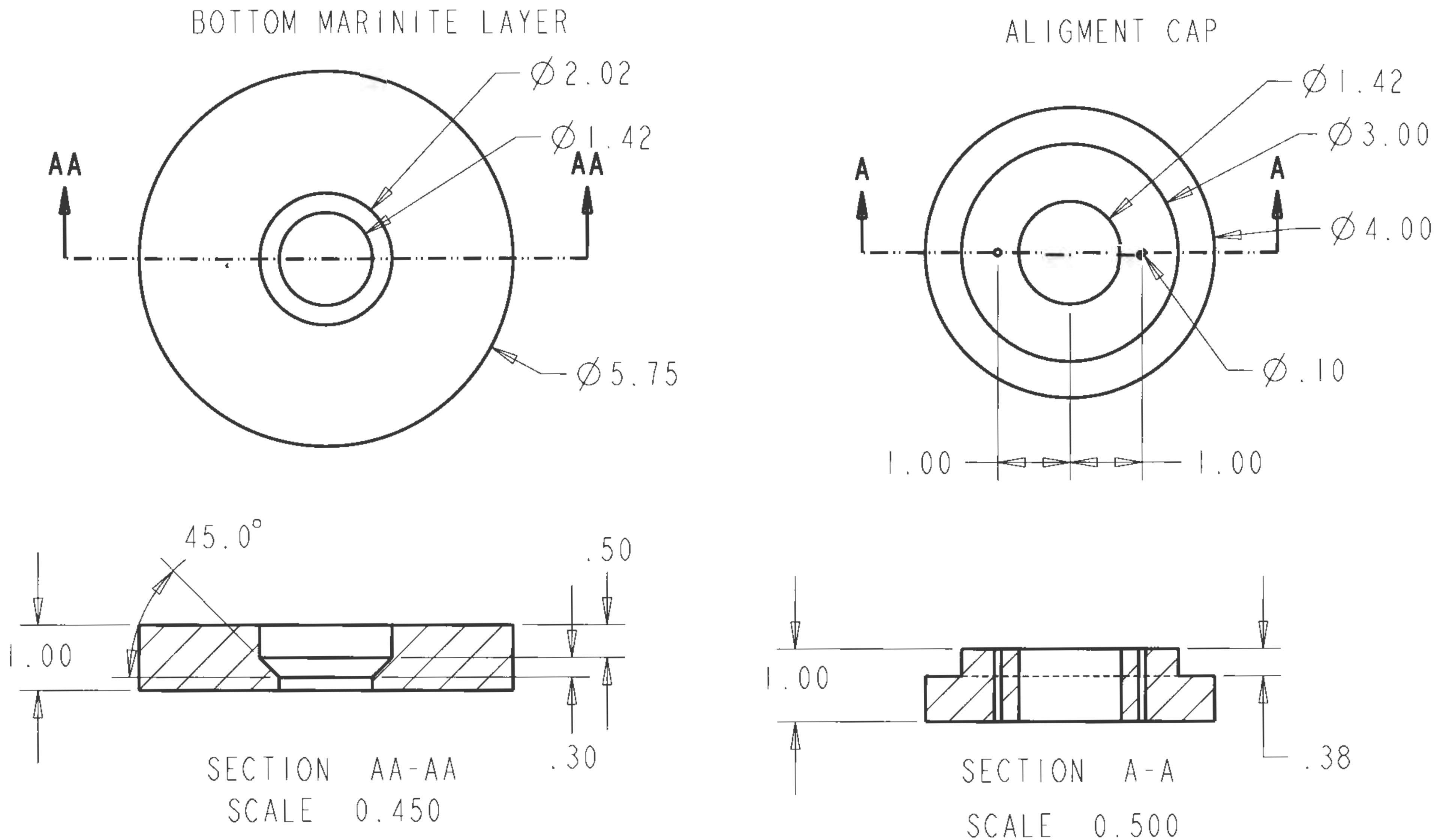
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE		
	SCALE: 0.2	REV:	
PART BASE PLATE	DATE: MAY 6 /01	QTY: 1	
MECHANICAL ENGINNERING UVIC	APPROVED BY:		



MUST BE MADE FROM PLATE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

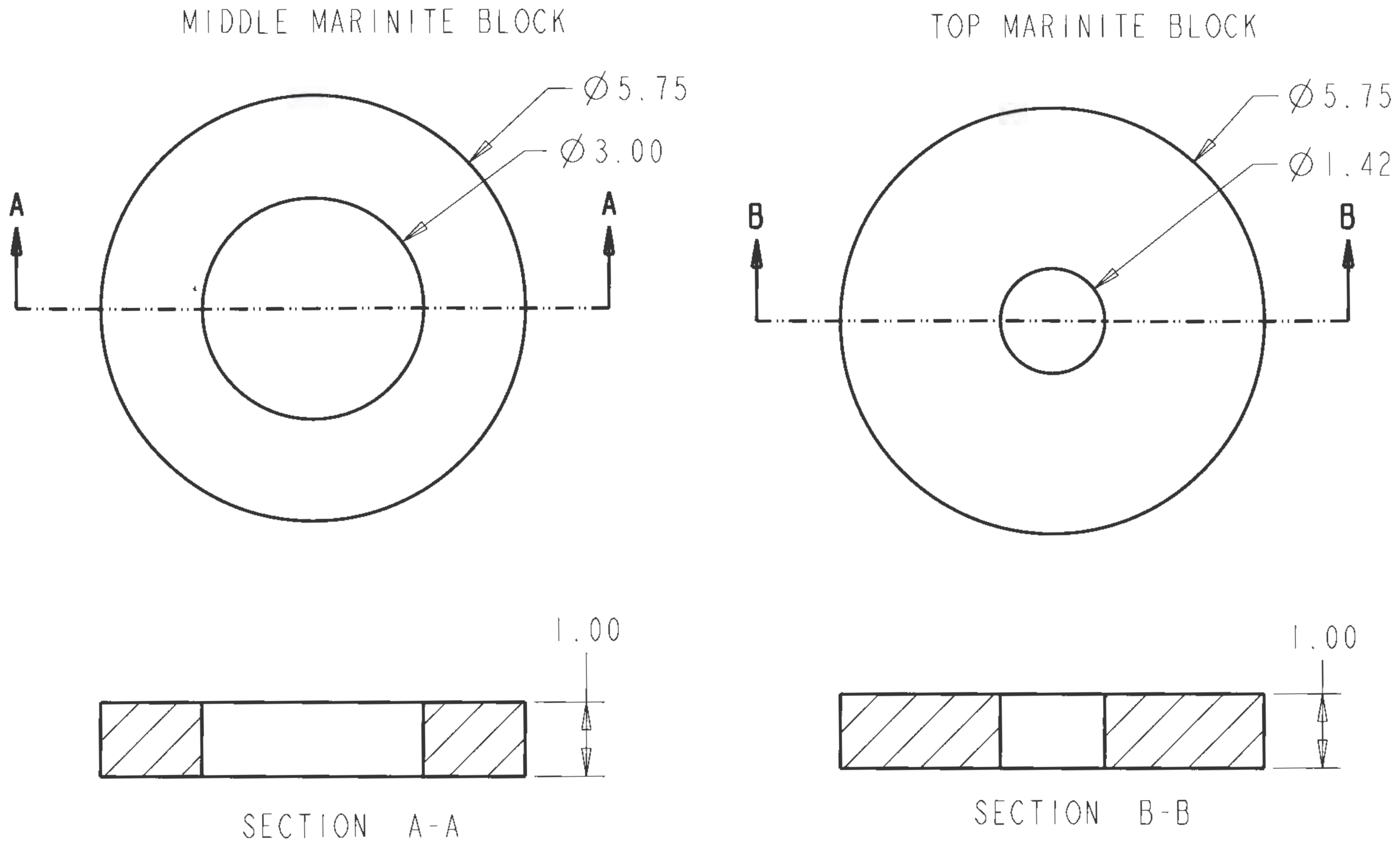
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 1.0	REV:
PART BOBBIN SHAFT	DATE: JUNE 1 /01	QTY: 5
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MADE FROM 1 in. MARINITE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE		
	SCALE: SEE NOTES		REV:
PART MARINITE PARTS (Bottom and Cap)	DATE: MAY 6 /01		QTY: 1
MECHANICAL ENGINNERING UVIC	APPROVED BY:		

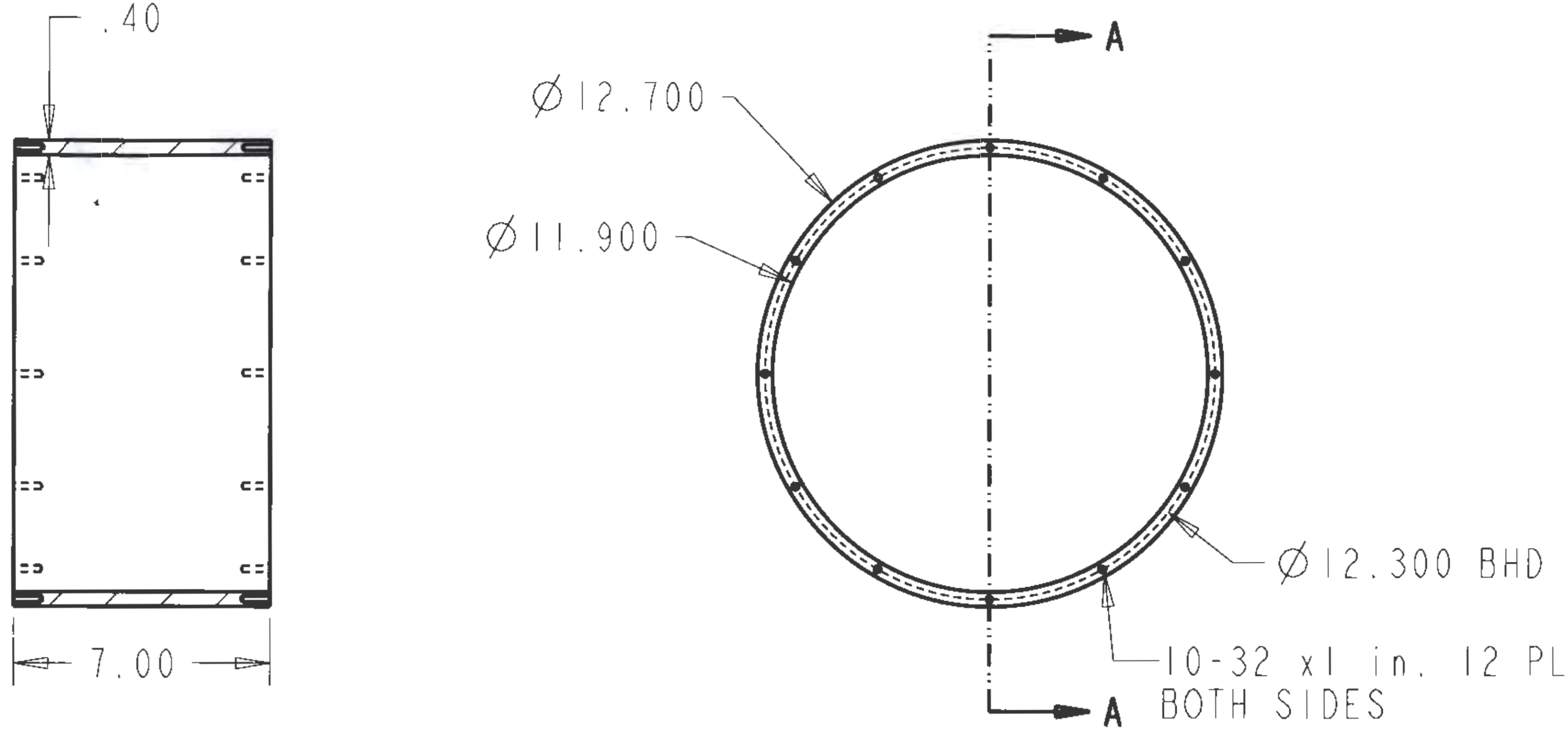


TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

MADE FROM MARINITE SHEET

PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.5	REV:
PART MARINITR PARTES (Top and Mid)	DATE: MAY 6 /01	QTY: 1
MECHANICAL ENGINNERING UVIC	APPROVED BY:	

CYLENDER

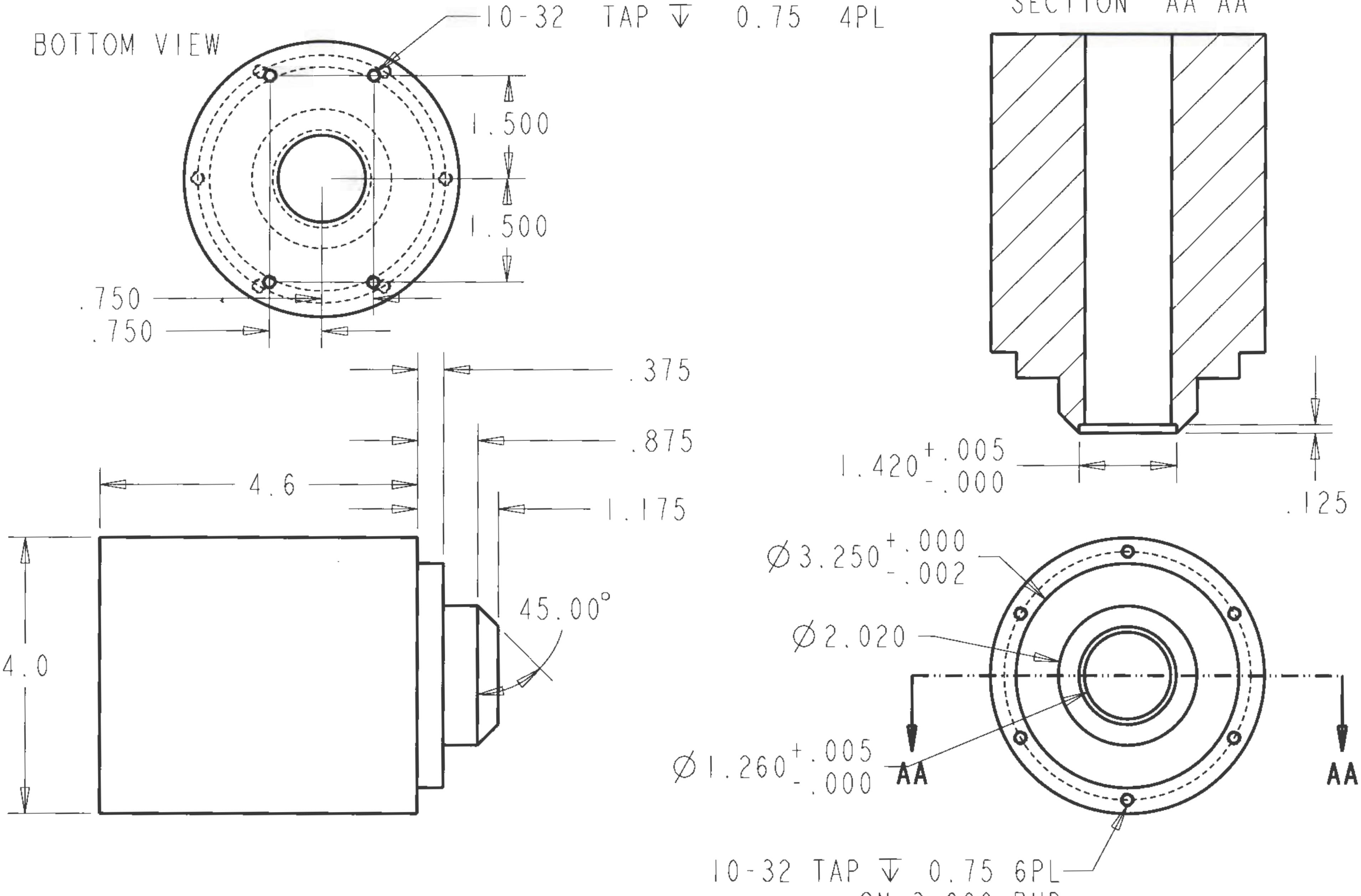


SECTION A-A

MADE FROM ALUMINUM

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

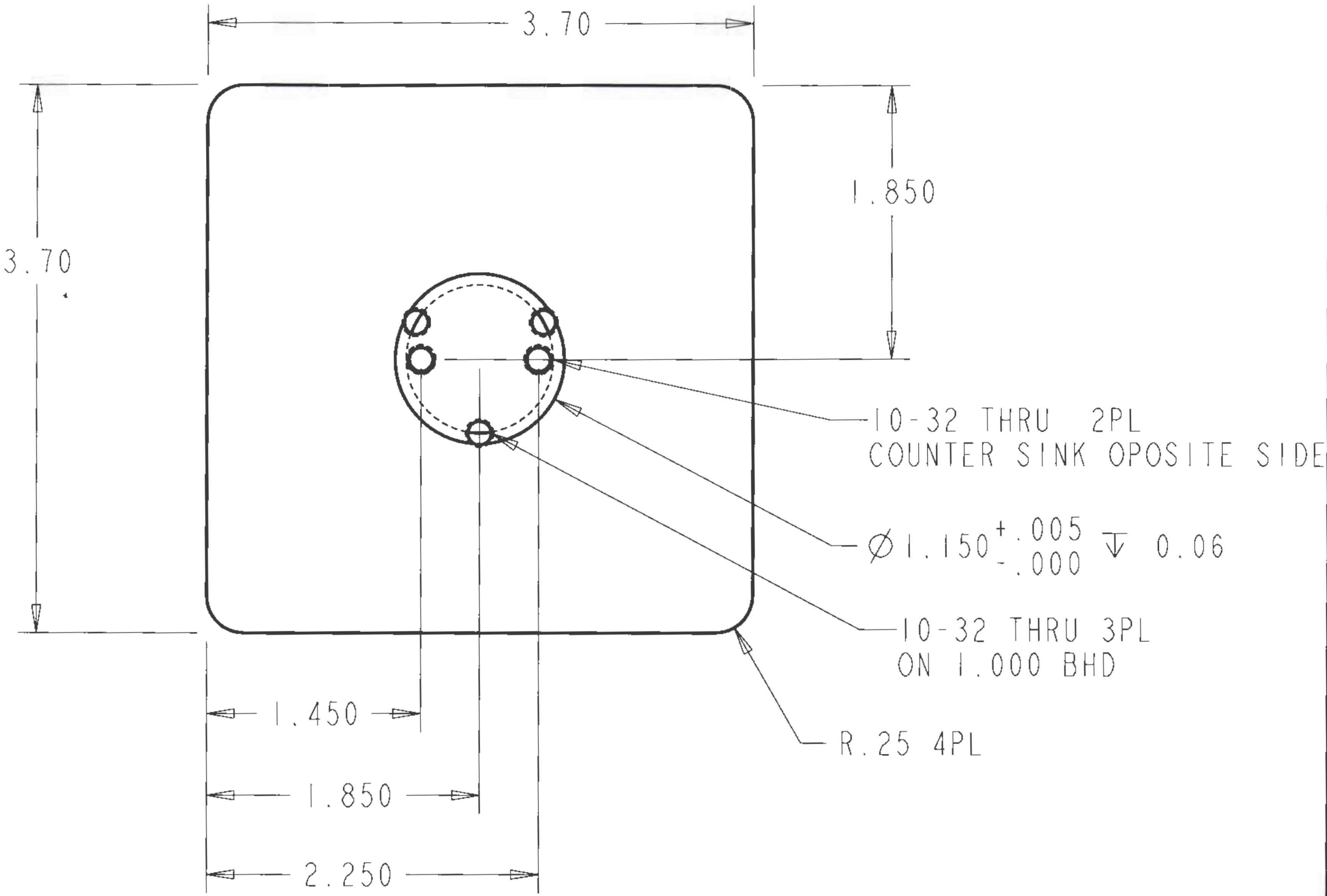
PROJECT CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
	SCALE: 0.2	REV:
PART CYLENDER	DATE: MAY 6 /01	QTY: 1
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MADE FROM ALUMINUM

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

PROJECT THM CdZnTe FURNACE	DRN BY: M. CROWLE	
	SCALE: 0.5	REV:
PART COOLING BLOCK	DATE: MAY 6 /01	QTY: 1
MECHANICAL ENGINNERING UVIC	APPROVED BY:	



MADE FROM PLATE1/4 in. PLATE

TOLERENCES
.X± .015
.XX± .01
.XXX± .005
UNLESS OTHERWISE SPECIFIED
REMOVE ALL SHARP
CORNERS AND BEBURR

PROJECT	CRYSTAL GROWTH THM	DRN BY: M. CROWLE	
		SCALE: 1.0	REV:
PART	BOBBIN FRONT PLATE	DATE: MAY 6 /01	QTY: 5
	MECHANICAL ENGINNERING UVIC	APPROVED BY:	

VITA

Surname: Crowle　　Given Names: Michael Richard

Place of Birth: Durban South Africa

Educational Institutions Attended:

University of Victoria	1998 to 2002
McGill University	1993 to 1998
John Abbott Collage	1990 to 1993

Degrees Awarded:

B.Sc.Eng.	McGill University	1998

Honours and Awards:

Olympic Torch Scholarship Fund Award	2000

Title of Thesis:

Equipment Designed for the Growth of CdZnTe Crystals by the Traveling Heater Method Under the Influences of Static and Rotating Magnetic Fields

Author

Michael R. Crowle
August 17, 2002