# Module Cover Conductivity Enhancement
# Senior Project

## Final Report

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## Abstract

A clam shell module cover for printed circuit boards (PCB) has been designed for use in Boeing's AECM cabinet. The cover utilizes materials with high thermal conductivity and cools the PCB by conducting the heat to a cold plate interface. Materials were compared and aluminum 6061-T6, aluminum 3003, and annealed pyrolytic graphite (APG) were chosen. A prototype was built and tested using aluminum 6061-T6 which was able to dissipate 57.7% of the projected wattage. Issues may include unforeseen complications in assembly along with components performing at lower levels than specified by manufacturers. The APG prototype was unable to be tested since it was not completed and shipped in time. Aluminum 3003 was found to be too scarce and expensive for the .75" plate needed for the prototype.

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# Nomenclature

**APG- Annealed Pyrolytic Graphite**: Graphite compound with very high thermal conductivity characteristics. (See S-4.5 Top Concepts)

**PCB – Printed Circuit Board**: A glass and copper board in which tracings are made in order for electrical components to work together without using wire strands to connect the components.

**Wort Chiller:** A wort chiller is a helical heat exchanger made from copper tubing. Water flows through the coils and through convection carries heat away from the system.

**EMC - Electromagnetic compatibility:** the ability to shield against electromagnetic interference (EMI) cause by other circuits, lightning, etc.

**Carbon Nanotubes:** Seamless cylinders derived from the honeycomb lattice that is a single atomic layer of crystalline graphite, called a graphene sheet.

# Section 1 - Introduction

With the increase of electronic components in aircraft, an efficient and economic means of cooling avionics becomes necessary. In the past, convection cooled cabinets were used to keep avionics functioning at an appropriate temperature. The industry is investing in alternative methods and materials for cooling, such as the use of conduction and a cold plate. This project's focus is to investigate the thermal capabilities of different materials through research and the testing of prototypes.

## S-1.1 Project Definition

This project has been assigned to four teams of California Polytechnic State University mechanical engineering students as their senior design project. The module cover enhancement team consists of Niles Dhanens and James Fortner. The primary stakeholder, The Boeing Company, is looking for an efficient, producible, low cost module cover design for their Advanced Equipment Cooling Method (AECM) avionics module. The AECM module cover safely secures electronics board so that they can quickly and easily be replaced within the cooling cabinet. The module covers must provide structural integrity, support high thermal conductivity, provide electro-magnetic shielding, secure the electronics board within, and interact with the cold plate interface in a simple but efficient operation. The module enhancement team will work closely with Mr. Charles Kusuda of The Boeing Company over the course of the next year to investigate and analyze new materials. An aluminum 6061-T6 prototype will be tested and results will be compared to the theoretical analysis done by The Boeing company. Notable variation between the results will constitute a redesigning of the testing operation. Other materials will also be selected for fabrication and testing. The results will be tabulated and analyzed with a full report submitted to Mr. Kusuda in December 2009.

## S-1.2 Motivation

The Boeing Company wants to invest in an alternative system for cooling avionics circuitry. Boeing would like to move from convection cooling cabinets to conduction cooling. Convection cooled cabinets are reaching a limit to the amount of heat that they can dissipate. The evolution of electronic systems is seeing smaller units with higher heat densities. The next generation of cooling devices must be able to handle the increase in heat from new electronic systems. Conduction cooling is a viable and efficient alternative to convection cooling. Conduction cooling using traditional materials does have a limit as well and alternative material research and development will be a large part of the next generation of cooling systems.

## S-1.3 Justification

This goal of this project is to verify the theoretical analysis done by The Boeing Company as well as consider and test alternative materials for the AECM module covers. Extra attention will be given to emerging technologies such as Annealed Pyrolytic Graphite (APG) and Carbon Nanotubes, which could greatly enhance the heat dissipation capabilities and reduce the weight of the module. This in turn would allow Boeing to use higher heat density electronics and larger electronics arrays in future aircraft.

### S-1.3a Transition from Convection to Conduction

Some believe that convection cooling has reached its maximum potential for cooling electronics systems. Boeing wants to move away from convection and towards conduction cooling since conduction systems are more efficient and can handle larger heat densities. Convection cooling systems rely on forcing air with a fan over the surfaces of electronics in order to carry the heat away (Figure 1). As electronics become smaller the power density increases, translating to a higher heat density of the electronics. Convection systems cannot accommodate the increase in heat density and therefore become obsolete. Air itself becomes an issue in convection systems. Air has a lower specific heat and lower thermal conductivity than non-compressible liquids. The fan for convection systems also serves as a problem point; convection systems have a limited rate of air flow. With higher heat densities from electronics, convection-cooled systems need to become larger to accommodate the increase in air flow. Conduction systems utilize sets of channels that cool the interface plates, or cold plates, of the electronics cabinet. The heat from the electronics is conducted to these cold plates and removed by the fluid being cycled through the channels. The focus of the module cover enhancement team will be to conduct the heat from the circuit board to the cold plate of the system, thus keeping the circuit board components at appropriate temperatures. Conduction systems are being used in this project because of the advantages conduction cooling provides. Since the flow of coolant is contained in the cold plate and does not need to be applied directly across the electronics, space between the PCBs can be minimized. Conduction cooling can also carry away more heat because non-compressible liquids have higher thermal conductivities and specific heats than air. The main limiting factor of the system

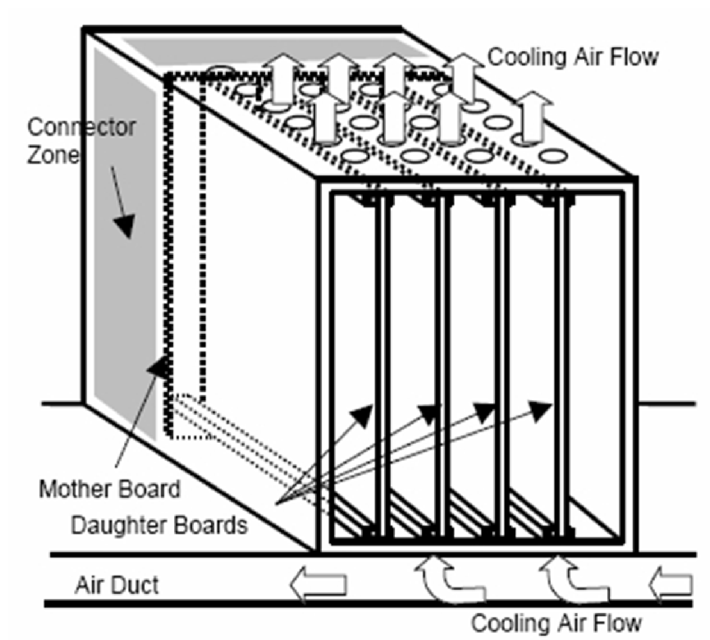


**Figure 1.** Typical geometry of a forced air convection electronics cooling cabinet.

then becomes the heat conducting materials. This problem has prompted extensive research into the development of new materials and the new designs in cooling. If an improved design is formulated, electronic cooling systems would have the ability to become more efficient and this in turn would benefit The Boeing Company.

**Cons of convection**

- Limited by airflow of fans
- Convection cooled electronics tend to accomadate low power densities and use large volumes of air
- Air has a low thermal conductivity
- Utilizes extended surfaces such as fins, heat spreaders, and heat sinks
- Airplanes have limited capacity for heat laden air produced by convection

**Pros of conduction**

- Non-compressible fluid has higher thermal conductivity air
- Able to handle higher heat loads
- Allows for smaller cabinet size
- Less audible noise
- Waste heat can be managed more easily

# Section 2 - Background

The Boeing 787 will utilize an all-electric architecture. This means the interface between the pilot's controls and flight control surfaces will be electronic as opposed to the traditional mechanical system. The increase in electronics of the 787 more than triples the heat generated in the larger 777's electronics. The electronics must be kept at acceptable temperatures in order to operate safely and efficiently. This trend of increasing quantities of electronics is indicative of a need for higher density packaging and improved cooling system capability to accommodate the increased cooling load. Specific areas researched include:

***Annealed pyrolytic graphite*** – an extremely thermal conductive material used in many modern heat sinks.

*****Carbon nanotubes*** – an emerging technology with unsurpassed thermal conductivity; approximately 15 times that of aluminum.

******Electromagnetic compatibility*** – the ability to shield against electromagnetic interference cause by other circuits, lightning, etc.

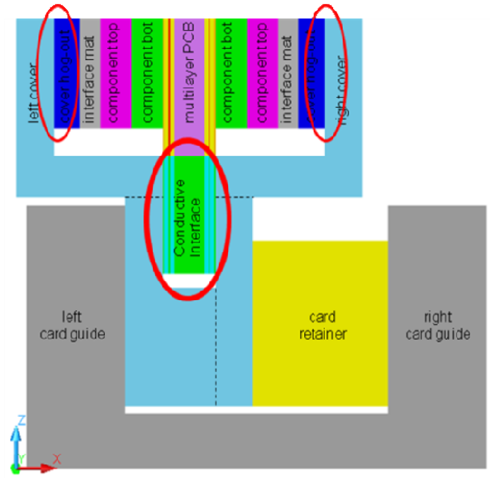


**Figure 2.** AECM module cover points of contact with circuit board

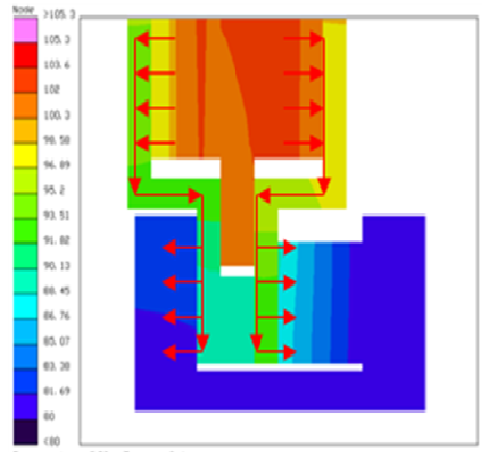

**Figure 3.** Heat Flow From Printed Circuit Board to Cold Plate Interface

* Carbon nanotubes were found to be too expensive to be included in this project.
** The EMC test was discarded due to time constraints.

## S-2.1 Project Design

The individual clam shell module covers in the Advanced Equipment Cooling Method (AECM) are meant to be replaced quickly and easily in case a problem arises. The module covers will be placed vertically into the cooling cabinet, connected to pins at the back of the cabinet, and clamped into place at the top and bottom (Appendix A, Figure A-1, A-2). Our team will specifically look at the conduction heat transfer of the module covers. The module cover surrounds the circuit board and can be seen as the pale blue material in Figure 2. The module cover does not directly touch the electrical components on the circuit board but rather contacts the printed circuit board through thermal interface materials. The module cover will interact with a layer of Therm-A-Gap 579/580 and contact a second interface material at the ends of the board. At the ends of the circuit board, the interface material will be pinched by the module cover. The points of contact where conduction will take place can be seen in red (Figure 2). At these points of contact, the module cover will conduct the heat generated by the circuit board to the ends of the module cover where conduction to the cold plate interface will occur (Figure 3). The heat will be dissipated by the cold plate interface (seen in dark blue) and the coolant will carry the heat away from the module cover. The AECM has specific dimensions and size requirements and an initial layout which the project will follow. However, there is room to make small size and shape modifications to the width of the module cover design if proper data and analysis shows a need for it. Blending materials such as composites with the metal casing may call for small modifications to the wall thickness. Reinforcements to reduce vibrations or strengthen the module may also be required, depending upon data gained from our testing and analysis.

## S-2.2 Notable Materials and Properties

### S-2.2a Annealed Pyrolytic Graphite

"Annealed pyrolytic graphite (APG) is a crystallographic carbon deposited on a substrate via the pyrolytic of a hydrocarbon gas" (Silverman). Annealed Pyrolytic Graphite is composed of tightly bonded, hexagonally arranged carbon layers that are held together with weak Van der Waals forces. The thermal properties of APG are truly astounding. APG has an in-plane thermal coefficient of approximately $1700\frac{W}{mK}$, whereas aluminum has a thermal coefficient of approximately $200\frac{W}{mK}$. APG is able to conduct about 8.5 times the amount of heat in-plane as aluminum, but unfortunately has low shear strength compared to metals. To solve this problem, the K-technology* company encapsulates the APG with a metal such as aluminum, copper, beryllium, or magnesium (Figure **4**). The high thermal conductivity of APG is limited to in plane flow. This means that the conduction of the heat out of the circuit boards to the module case would be very poor. However, the use of thermal vias discussed later in the report provides a potential solution to this problem. Choosing APG depends on many factors such as cost and availability. Because this is a custom project, the machining and production for an APG unit with aluminum coating will have to take place at the manufacturer's factory.

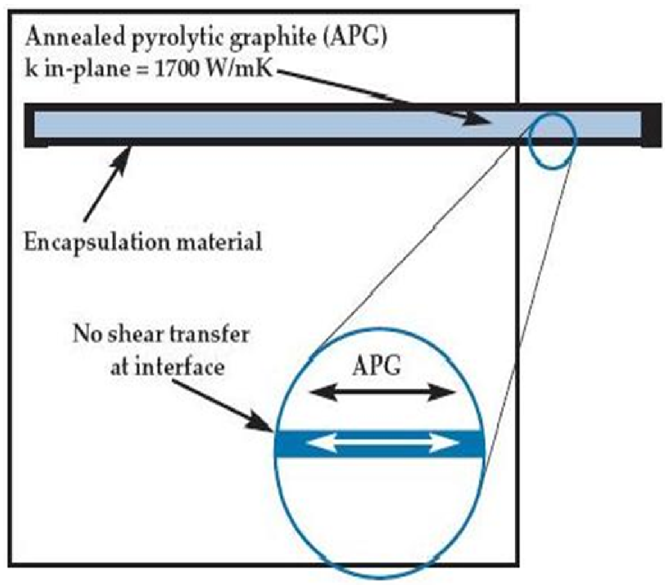


Figure **4.** Patented APG encapsulation patented by K-Technology Corporation. APG is encapsulated with structural material to ensure the structural integrity of the part

*K-technology underwent a merger during the course of this project

### S-2.2b Carbon Nanotubes

Carbon nanotubes are essentially seamless cylinders derived from the honeycomb lattice that is a single atomic layer of crystalline graphite, called a graphene sheet (Dresselhaus, 3). Multiwall carbon nanotubes are also being used to produce stronger nanotube structures. Carbon nanotubes have a very high strength to weight ratio. Carbon nanotubes have about 5 times the tensile strength of aluminum and about half the density. They are also very thermally conductive and have been estimated to conduct about 3000$\frac{w}{mK}$. This is 15 times more conductive than aluminum and 1.75 times as thermally conductive as Annealed Pyrolytic Graphite. The characteristics of carbon nanotubes are extremely good; however, the process to produce carbon nanotubes is extremely difficult and expensive. In order to use carbon nanotubes effectively they must be grown in the desired orientation. They are made through the process of Arc-Discharge or Laser Ablation. Arc-Discharge uses the evaporation of carbon atoms. The atoms are evaporated by plasma of helium gas that is ignited by high currents passed through carbon anode and cathode. The carbon tubes are held together by Van der Waals bonds and produce tight bundles. The defects of the structure are minimized on the sidewalls of the tubes. Laser Ablation uses intense laser pulses to vaporize a carbon target that is placed in a 1200$^{o}$C oven. An inert gas is then passed through the oven chamber to carry the grown nanotubes away to be collected. Carbon ropes are produced by this process and are packed into hexagonal crystals, held by Van der Waals bonds.

The major drawback of carbon nanotubes is the difficulty of production. The time, cost, and difficulty of producing carbon nanotubes is very high. Because of the impurities that occur in the growing process, the properties of the sheets differ along the length of the material. One source showed that carbon nanotubes are sold in small squares starting at $250, making them the most expensive material. The reason for this small area is due to the difficulty in producing large amounts of efficient carbon nanotubes, making mass production a problematic concept. They are also produced as a thin layer onto a surface, so suppliers would need to be contacted if a certain material was desired for the base. Carbon nanotubes are also thermally conductive only along the grain. With this in mind, the heat flow of carbon nanotubes is very dependent on design. This means carbon nanotubes cannot be used as the sole material for module cover.

An alternative to using carbon nanotubes as the sole material for the module cover is to use carbon nanotubes in conjunction with an epoxy and attach the carbon nanotubes to an existing module cover. More information is required before making an informed decision about pricing as well as our ability to integrate it with our specified design. Manufacturers will be our primary source of information for availability and cost as this subject is being pursued.

A distributor called Carbon Solution has been found in Riverside, California. Prices start at $50 per gram in their unrefined form (about 50% efficient) and go up till $400/100mg for refined carbon nanotubes (about 90% efficient). Orientation affects the thermal conductivity of nanotubes, and it is predicted that finding someone to arrange them on the module cover would only increase the price especially since Carbon solution does not align the nanotubes in house.

### S-2.2c Electromagnetic Compatibility

Electromagnetic interference (EMI) must be accounted for in the design due to the close proximity of the printed circuit boards. Modern digital processing methods use fast pulses of energy to code and decode information. These pulses run high clock rates (several tens of megahertz) over short transition times (sometimes only a few nanoseconds). On printed circuit boards this can cause what is known as coupling, or "cross talking," between adjacent modules. These fast pulses can also activate harmonic frequencies which transmit even more power over shorter transition times. Due to coupling and the possibility of harmonic frequencies, electromagnetic compatibility (EMC) must be incorporated into the design. Lightning strikes may also cause EMI and must be simulated in testing.

One form of EMC is shielding, which reduces coupling of adjacent circuit boards due to unintentional electromagnetic fields. Shields work by surrounding the equipment with conductive material which converts the electromagnetic fields to a current; much like an antenna converts electromagnetic waves (radio waves) back to a current. Shielding works best for high frequency EMI, so it is an appropriate choice for protecting printed circuit boards. The shielding performance is affected by seals, joints, and openings in the shield and must be considered in the module cover production.

# Section 3 - Objectives

Currently, the thermal analysis for Boeing's AECM is all theoretical. After selecting appropriate materials, models will be built for testing. The primary objective is to build and test the proposed Boeing design of aluminum 6061-T6 module cover with Therm-A-Gap 579/580 thermal interface material to verify the theoretical analysis (Appendix B, Figure B-1, B-2). The other materials will then be tested in thermal conductivity, structural integrity, electromagnetic shielding, cost, and manufacturability. The specifications that are listed below were developed through discussion as well as the documentation by provided Charles Kusuda.

## S-3.1 Scope of AECM Module Cover Enhancement Project:

- Investigate the properties of alternative materials to aluminum 6061-T6
- Construction of Prototypes
- Analysis and Testing of Materials
- Vibration Testing*
- Strength Analysis*
- Thermal Testing
- Electromagnetic Shielding Testing*
- Analysis of information gained from tests and recommendations

  * Discarded to make time for thermal testing

## S-3.2 Design Criteria

- High thermal conductivity compared to 6061 Aluminum
- Low weight compared to 6061 Aluminum
- Low cost compared to 6061 Aluminum
- High manufacturing capabilities compared to 6061 Aluminum
- Adhere to aircraft standards provided by Boeing for Front EE Bay (Zone 1)
- D6-81926 BCA Equipment Vibration Test Requirements ( (Hansen))
- D6-16050-5 Electromagnetic Interference Control Requirements for Composite Aircraft (Skala)
- Keep printed circuit board temperature (PCB) below 105°C
- Have a life of 20 years

## S-3.3 Quality Function Deployment

In order to make sure all the customer's needs were met, a quality function deployment (QFD) diagram was created (Figure 5). The customer needs, which included heat dissipation, cost, manufacturability, EMI shielding, structural integrity, and weight, were weighted to show their importance to the project as a whole. After reading the literature supplied by The Boeing Company, some target values were developed and entered under the engineering requirements. To meet all the customer needs attention was given to material selection, production of a prototype, and testing of the prototype. The results from the QFD were used to narrow the materials we researched and to specify which material properties were to be considered.

**AECM Module Cover Conductivity Enhancement QFD**

| | | Weighting | Thermal Conductivity | Material Selected | Prototype | Vibration Testing | Strength Testing |
|---|---|---|---|---|---|---|---|
| | | **Engineering Specifications** | | | | | |
| **Customer Requirements** | Heat Dissipation | 25 | 9 | 3 | 1 | | |
| | Cost | 20 | | 9 | 3 | | |
| | Manufacturability | 10 | | 9 | 3 | | |
| | EMI Shielding | 5 | 1 | 9 | 3 | | |
| | Structural Integrity | 5 | | 9 | 1 | 3 | 9 |
| | Low Weight | 5 | | 9 | 1 | 1 | |
| | **Units** | | W/m*C | | | Random Noise | psi |
| | **Target** | | >155.8 | | | 5 hours | |

**KEY**

| | |
|---|---|
| **9** | Strong Correlation |
| **3** | Medium Correlation |
| **1** | Small Correlation |
| **Blank** | No Correlation |

**Figure 5.** Quality function deployment diagram used to convert customer requirements into engineering specifications.

## S-3.4 Engineering Specifications Table

Using the QFD, project specifications were defined and distinguished from the project goals. An engineering specifications table was created (Table 1) as a way to quickly identify the engineering specifications, identify the predicted target and tolerance, identify the risk the specification holds for achieving customer satisfaction, and list the method(s) to be used for verification. The engineering requirements (below) are a list of additional design considerations that will be considered throughout the project.

**Table 1.** Formal Engineering Requirements

| Spec # | Parameter Description | Requirement or Target | Tolerance | Risk | Compliance |
|---|---|---|---|---|---|
| 1 | Temperature | <105 C | Max | H | A, T |
| 4 | Geometry | 0.075 inches | ±.01 inches | L | I |
| 5 | Density | .098 lb/in^3 | +.025 lb/in^3 | M | A |
| 6 | Cost | $18 per sheet | ±$5 per sheet | H | I |
| 7 | Vibration | Extensive test specified in doc | Pass/fail | M | T |
| 8 | EM Shielding | EIM present | Pass/fail | M | I |

**Key:** H – High M – Medium L – Low
A – Analysis T – Test S – Similar to existing designs I – Inspection

## S-3.5 Design Considerations for the AECM Module Cover Enhancement Project

- Analysis
  - Thermal Conductivity
  - Structural*
    - Strength
    - Life (20 years)
  - Vibration*
  - EMC/EMI*

* Discarded to make time for thermal analysis

- Prototypes
  - Construction
    - Adhere to the configuration 2 dimensional specifications as specified in AECM LRU Drawing_5 Document (Appendix A, Figure A1, A2 )
      - Only the overall width of the cover (0.693in) may be modified for testing
      - Proper analysis and reasoning must be provided to warrant change
    - Exotic Thermal Materials
    - 6061 Aluminum

- Testing
    - Thermal Conductivity
        - Accommodate approximately 239 Watts of heat while in operation
    - Structural*
    - Vibration*
    - EMC/EMI*
- Verification of theoretical data
- Comprehensive report of findings with recommendations submitted to Charles Kusuda

  * Discarded to make time for thermal testing

# Section 4 – Design Development

## S-4.1 Ideation

To begin the decision process, a specifications table (Table 1) was drafted to list all the requirements of the module cover. The requirements were then organized in a QFD diagram (Figure 5) and converted into rough engineering specifications. Thermal conductivity was considered to be the key material property since it was directly related to the fundamental function of the project. If the printed circuit board is not maintained at a temperature below 105 degrees Celsius the board will fail. An initial look at the thermal capabilities of different materials was done and any material around the thermal conductivity of aluminum was considered (see Table 2). After presenting the list to Mr. Kusuda, he suggested the addition of carbon nanotubes and Annealed Pyrolytic Graphite. A new list was developed and taken to Dr. Trevor Harding, a Materials Engineering professor on campus in order to get more information about the chosen materials. Dr. Harding explained that while the materials we listed all had relatively high thermal conductivity, but aluminum was an excellent choice when availability, cost, weight, and strength characteristics were considered. By his suggestion we added the other blends of aluminum to the list of materials being considered.

Once the thirteen materials shown in the Materials Considered section were selected, a decision matrix was developed (Figure 6). The decision matrix was used to rate each material and a decision was made that the module covers would be designed, manufactured, and tested using the top two rated materials along with the proposed aluminum 6061-T6.

## S-4.2 Materials Considered

- Aluminum 6061-T6
- Copper
- Gold
- Silver
- Beryllium
- Magnesium
- Annealed Pyrolytic Graphite
- Thermal Plastic (Parker)
- Aluminum 7075-O
- Aluminum 2024-O
- Aluminum 7079-T6
- Aluminum 3003
- Carbon Nanotube Matrices

## S-4.3 Materials Compared to Aluminum 6061-T6

Most materials listed above were chosen because their thermal conductivity was equal to or greater than that of 6061 aluminum. Annealed Pyrolitic Graphite and matrices impregnated with carbon nanotubes were specifically mentioned as topics of interest by the Boeing Company. Parker's Thermoplastic was initially considered because of its EMC capabilities and since Parker mentioned its use in heat sinks. As Table 2 shows below however, it lacks the thermal conductivity necessary to be the sole material of the module cover.

**Table 2.** The density, thermal conductivity, and best estimate of a comparative price for each material listed above.

| Material | Price | Density (kg/m^3) | Thermal Conductivity (W/m*C) |
|---|---|---|---|
| **Aluminum 6061-T6** | ~ $15 - 1'x2'x1/16" | 2700 | 167 |
| **Copper** | ~ 5 times AL 6061 | 8900 | 392.9 |
| **Gold** | ~ 6.25 times AL 6061 | 19320 | 297.7 |
| **Silver** | ~ 5.625 times AL 6061 | 10500 | 417.1 |
| **Beryllium** | ~ 3 times AL 6061 | 1850 | 147.1 |
| **Magnesium** | ~ 2 times AL 6061 | 1770 | 114.2 |
| **Annealed Pyrolytic Graphite** | *** | 2260 | 1700i-dir ; 1700j-dir ; 10k-dir |
| **Carbon Nanotubes** | > $50/gram | -- | 1400 |
| **Thermoplastic A240-HTHF** | *** | 1400 | 0.7 |
| **Aluminum 2024-T3** | ~ same as 6061 | 2770 | 190.4 |
| **Aluminum 7079-T6** | ~ same as 6061 | 2740 | 121.1 |
| **Aluminum 3003** | ~ same as 6061 | 2700 | 233.64 |
| **Aluminum 7075-0** | ~ same as 6061 | 2810 | 173 |

| **KEY** | |
|---|---|
| Red Text | Best Estimate |
| *** | Contact Supplier |
| -- | Negligible |

## S-4.4 Decision Matrix

Once the list of materials being considered was developed (Table 2) a new weighting system was developed with the help of Mr. Kusuda to rate each material based on their density, cost, manufacturability, and thermal conductivity. Aluminum 6061-T6 was used as the datum to compare the selected materials against since it's called for in the original design. The manufacturing consideration includes price, availability, processing time, and safety to the environment and the production workers.

The results of the decision matrix (Figure 6) shows that Annealed Pyrolytic Graphite and aluminum 3003 are both candidates for a new module cover. Since The Boeing Company has already done extensive testing on aluminum, approval was sought from Boeing before any other blend of aluminum was considered. Aluminum 3003 was found to be an acceptable material for further research and was specified for use in prototype fabrication and testing.

A supplier as been found for the carbon nanotubes, however they are extremely expensive and would be used as an addition to another material.

**Materials**

| Design Criteria | Weighting Factor | Aluminum 6061 | Copper | Gold | Silver | Beryllium | Magnesium | Annealed Pyrolytic Graphite | Carbon Nanotubes | Thermoplastic A240-HTHF | Aluminum 2024-T3 | Aluminum 7079-T6 | Aluminum 3003 | Aluminum 7075-O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low Cost | 30 | 0 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | | -0.2 | -1 | 1 | |
| Low Density | 20 | 0 | -1 | -1 | -1 | 1 | 1 | 1 | 0 | 1 | -0.1 | -0.1 | 0 | -0.1 |
| Manufacturability | 15 | 0 | 0 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Thermal Conductivity | 35 | 0 | 1 | 1 | 1 | -1 | 1 | 1 | 1 | -1 | 1 | -1 | 1 | 1 |
| ∑+ | | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | 2 | 1 |
| ∑- | | 0 | 3 | 4 | 4 | 3 | 2 | 3 | 2 | 2 | 1.3 | 4 | 1 | 1.1 |
| Total | 100 | 0 | -15 | -30 | -30 | -60 | 10 | 40 | 20 | 1 | 27 | -67 | 65 | 33 |

**Figure 6.** Decision Matrix used to rate materials against Aluminum 6061-T6.

Key

| | | |
|---|---|---|
| -1 = Worse | 1 = Better | 0 = Same |
| * = NA, Enhancement | Blank = Unknown | |

## S-4.5 Initial Concepts

### S-4.5a Annealed Pyrolytic Graphite

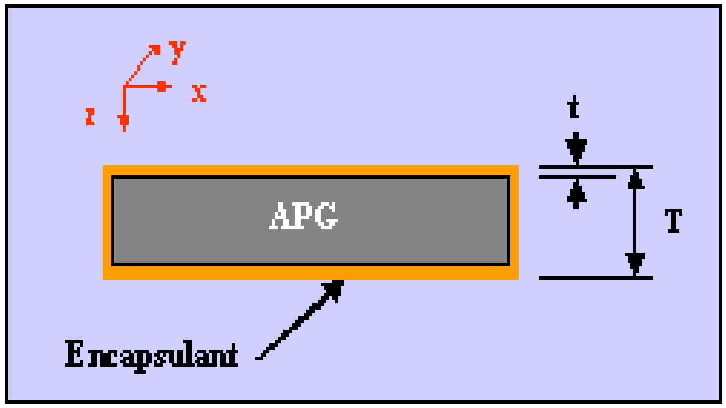


**Figure 7.** The APG material coated in another material (aluminum for this project).

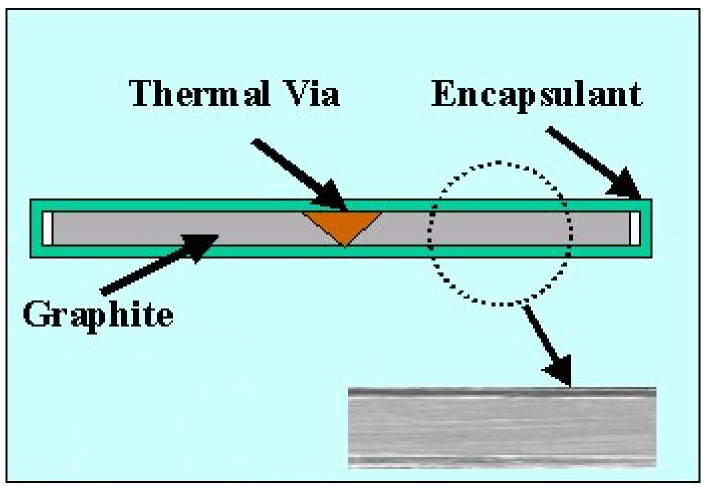


**Figure 8.** Cross section view of the encapsulated APG that is utilizing a thermal via to maximize heat transfer in the in-plane direction from the metal.

The first concept for the project is annealed pyrolytic graphite with an aluminum coating (Figure 7). APG has a higher thermal conductivity of aluminum; however, the sheer strength of APG is much lower than metals. The APG composite must therefore, utilize a metal case to provide structural support for the component. APG has extremely good heat transfer along its grains, but not through the material's thickness. Figure 8 shows a side view of the APG material encased within another material. The K-Technology website allows a user to specify the encapsulating material, wall thickness, and total thickness of the casing and then provides the density and thermal conductivity of the unit in the x, y, and z–directions axes shown in Figure 9. The thermal conductivity of an aluminum 6061-T6 module cover is approximately 200$\frac{w}{mk}$. With this information, it can be seen that an APG insert of only 0.015in, based upon our specified module cover wall thickness, will double the thermal conductivity of the unit in the x and y-directions. Unfortunately, APG does not conduct heat well in the z-direction. This means that if the APG was used in the configuration seen in Figure 7, the conduction of heat from the printed circuit board would not be transferred well through the depth of the APG. The advantages of using APG depend upon getting the heat to flow along the grains, therefore depending upon the conduction properties of APG in the z-direction it may be counter-productive and provide a lower thermal conduction compared to aluminum (Figure 10). However, an alternative design can be used. Metal crossing from the inner to outer wall of the casing can be designed in the case, splitting the APG sheet. These vias (Figure 11) allow for heat flow in the z-direction from the circuit board to the aluminum of the module cover and around the APG. The vias then transfer the heat in the x and y-directions (in-plane directions) along the

APG. This solves the problem of low conductivity of the APG in the z-direction. The heat will simply flow around the APG and then flow through the grains, maximizing heat transfer.

| **Encapsulating Material: Aluminum** | | |
|---|---|---|
| **t (wall thickness): 0.03in** | | **T (total Thickness):** 0.075in |
| **w (APG thickness): 0.015 in** | | **Density:** $2.61 \frac{g}{cm^3}$ |
| $k_{xx} = 484 \frac{W}{mK}$ | $k_{yy} = 484 \frac{W}{mK}$ | $k_{zz} = 61.69 \frac{W}{mK}$ |

**Figure 9.** A theoretical calculation of a module cover with inserted APG of 0.015 in thickness. Thermal conductivity is approximately doubled in the x and y-directions. Courtesy of the k-Technology website.

A potential problem with using APG is the fact that the wall of the casing must now have sections machined out of it. This could potentially cause failures in the material during the shock or vibration of normal use. Testing of the case is essential to being able to guarantee the success and 20 year life rating of the module cover. Boeing has expressed a desire to use exotic materials such APG and therefore small modifications to case geometry will be allowed, if improvement to the performance of the unit is significantly enhanced. A modification such as thicker walls is a possibility due to the fact that APG must be inserted in to the walls of the casing and the structural integrity of the casing may be compromised.

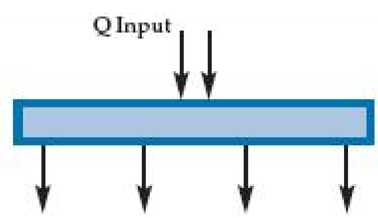


**Figure 10.** Encased APG design, which will does not reduce the amount of thermal conductivity in the z-direction (direction of arrows in figure).

Mr. Montesano, Vice President of K-Technology and co-author of the Annealed Pyrolytic Graphite encapsulation patent in other materials, has agreed to allow the use of his company’s product in our testing as long as we report our findings back to him. He has graciously supplied scrap samples of pure APG for some initial strength testing. Once a cover design has been developed, we will work with K-technology to produce an actual prototype.

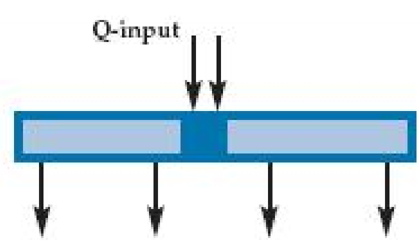


**Figure 11.** Alternative design of APG encasement using vias to enhance thermal conduction in the z-direction (directions of arrows in figure).

Annealed Pyrolytic Graphite is an excellent candidate material that will be incorporated in the final design of the AECM module covers. APG’s thermal conductivity properties are very high and the potential problem with heat flow can be avoided.

Testing and a new cover design will be essential to determining if APG can be used in future module covers.

### S-4.5b Aluminum 3003

During the design phase of this project, the choice of 3003 aluminum seemed like a viable choice. It possesses higher thermal conductivity than 6061 aluminum and is can easily be machined. Although strength was not a major design criterion, we believed that the material would allow the module to be functional for a life of 20 years.

**Reason for not being chosen for final concept**: We assumed that aluminum 3003 was readily available because of the its wide range of uses such as in soda cans. However, each module cover side needs to be machined from a single plate of aluminum. In order to do this, 0.75" plate of 3003 aluminum needed to be used for manufacturing each module cover. Upon further research, aluminum 3003 is readily available in sheets under 0.25" in thickness but not 0.5"or above. Plates of 0.75" thickness are specialty items and only a few manufacturers produce plates of this thickness. The cost of purchasing these plates would be upwards $1000. Due to the high cost of these plates, we as a team discussed this with our project advisor and decided to exclude aluminum 3003 as a material for our final design concept.

### S-4.5c Aluminum 6061-T6

Along with our top concepts, aluminum 6061-T6 will be prototyped and tested. Empirical data matching the analysis provided by the Boeing Company will merit our test fixture validity. Failure to produce similar results will allow us to identify and correct any faults in our test bench design. Comparing the analytical and empirical data will also allow us to calculate a percent error for our tests.

## S-4.6 Initial Thermal Test Fixture Concept

Thermal conductivity is the critical characteristic being investigated in this project. To test the AECM module cover, the environment that the module cover will operate in must be recreated. To do this the test fixture that is seen below was developed.

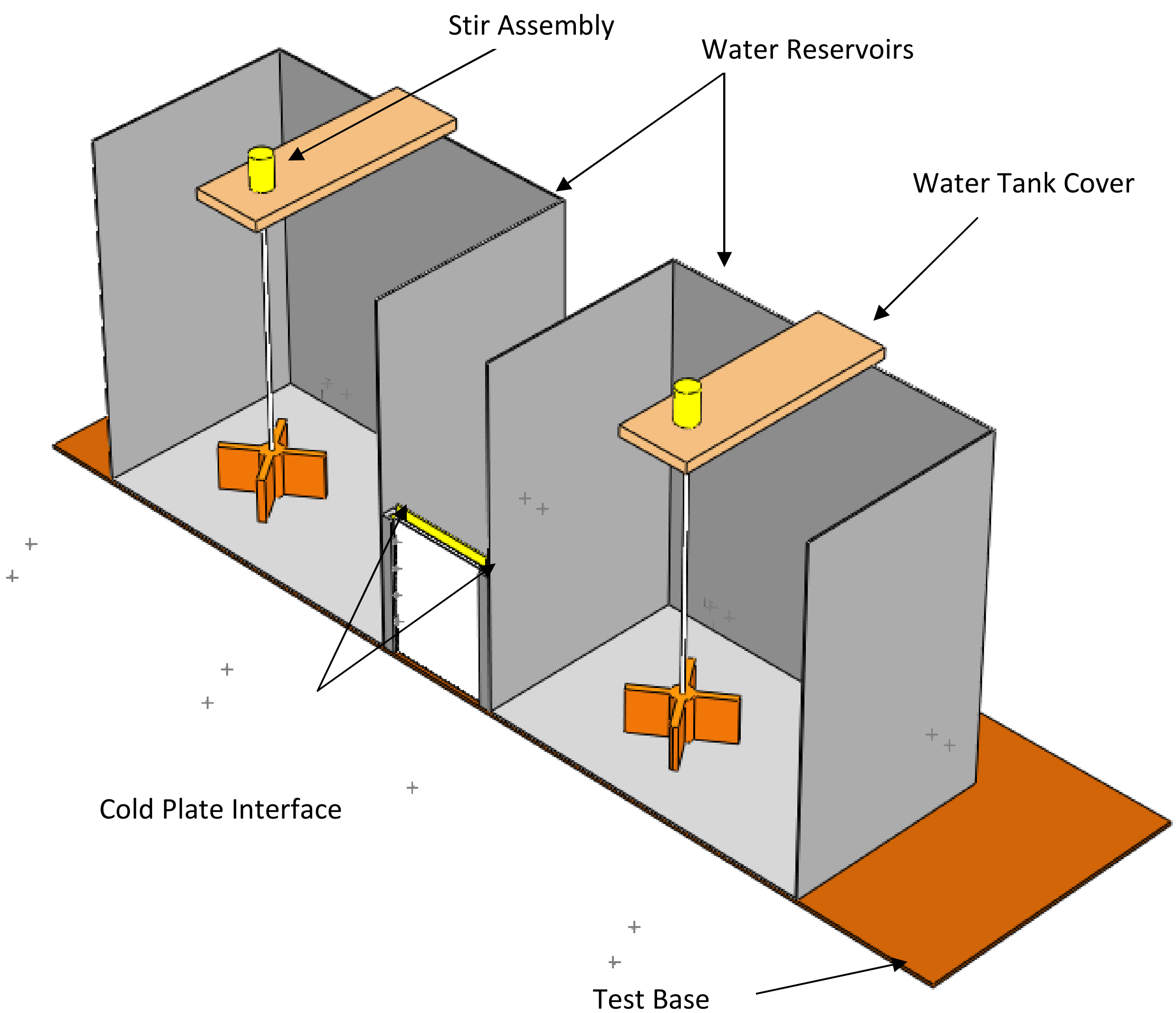


**Figure 12.** Cross section of the thermal test fixture.

### *Cold Plate Interface*

The module cover interface is based upon the cold plate interface depicted in the actual AECM cabinet. U shaped slots will be machined out of aluminum 6061 and attached to the water reservoirs using JB weld. The module cover will be clamped into the U shaped slots using Birtcher clamps as specified by Boeing. This orientation allows heat to flow from the module cover into the U shaped interface and into the water reservoirs.

### *Water Reservoirs*

The water reservoirs for the thermal testing bench will be made of metal and have a volume of 6 gallons. A cooling coil know as a wort chiller (Not shown in drawing, see appendix E) will circulate cold water inside the tanks as desired to control the temperature. Water tanks will be placed on both sides of the AECM module cover as shown in Figure 13. They will act as the cold plates shown in the Boeing analysis and dissipate the heat produced by the strip heaters. The water tanks will be kept at a constant temperature through diligent measurements taken on the U shaped cold plate interface and adjustments will be made by running cold water through the wort chiller. Multiple tests will be run different water temperatures ranging between 70 and 80 degrees Celsius.

### *Module Cover Insulating Box*

The module cover insulating box will fit around the module cover assembly and the Interface clamping blocks which are attached to the water tanks. The insulating box will fit flush with water tanks in order to keep the cooling of natural convection and radiation to a minimum. The box will be of a material with adequate radiation shielding. It is important to note that the module cover insulating box is not seen in the assembly drawings provided because it would cover the module cover assembly.

### *Stirring Module*

If preliminary testing shows the need for faster heat dissipation, stirring modules will be added (one per tank). These stirrers will increase the convection between the tanks and the water, thus drawing heat away from the interface at a higher flux. The modules will consist of a motor, stirring rod, and power source. Mounting supports will be built out of wood to hold the motors over the tanks.

### *Test Base*

The test base will be a plywood sheet which will enable easy movement of the entire test apparatus so that it may be transported and all test parts can be safely secured. It will also keep the reservoirs in fixed locations and provide consistency for all the tests.

### *Birtcher Clamps*

Clamps will be purchased from Birtcher and are specified in the bill of materials (Table 3). In order to follow our specified timeline, a shorter clamp than that specified in Boeing's initial analysis, may need to be purchased because of availability issues.

# Section 5 - Final Module Cover and Test Fixture Designs

The design for the module covers, thermal test fixture, and vibration test fixture are outlined in the following section. A testing schedule and manufacturing flowcharts have been developed for each system. It is important to note that the aluminum 6061-T6 prototype will be used to test and tune our testing fixtures to achieve conditions as close to those specified by Boeing as possible.

## S-5.1 6061 Aluminum AECM Module Cover Design

### S-5.1a Aluminum 6061 Final Design

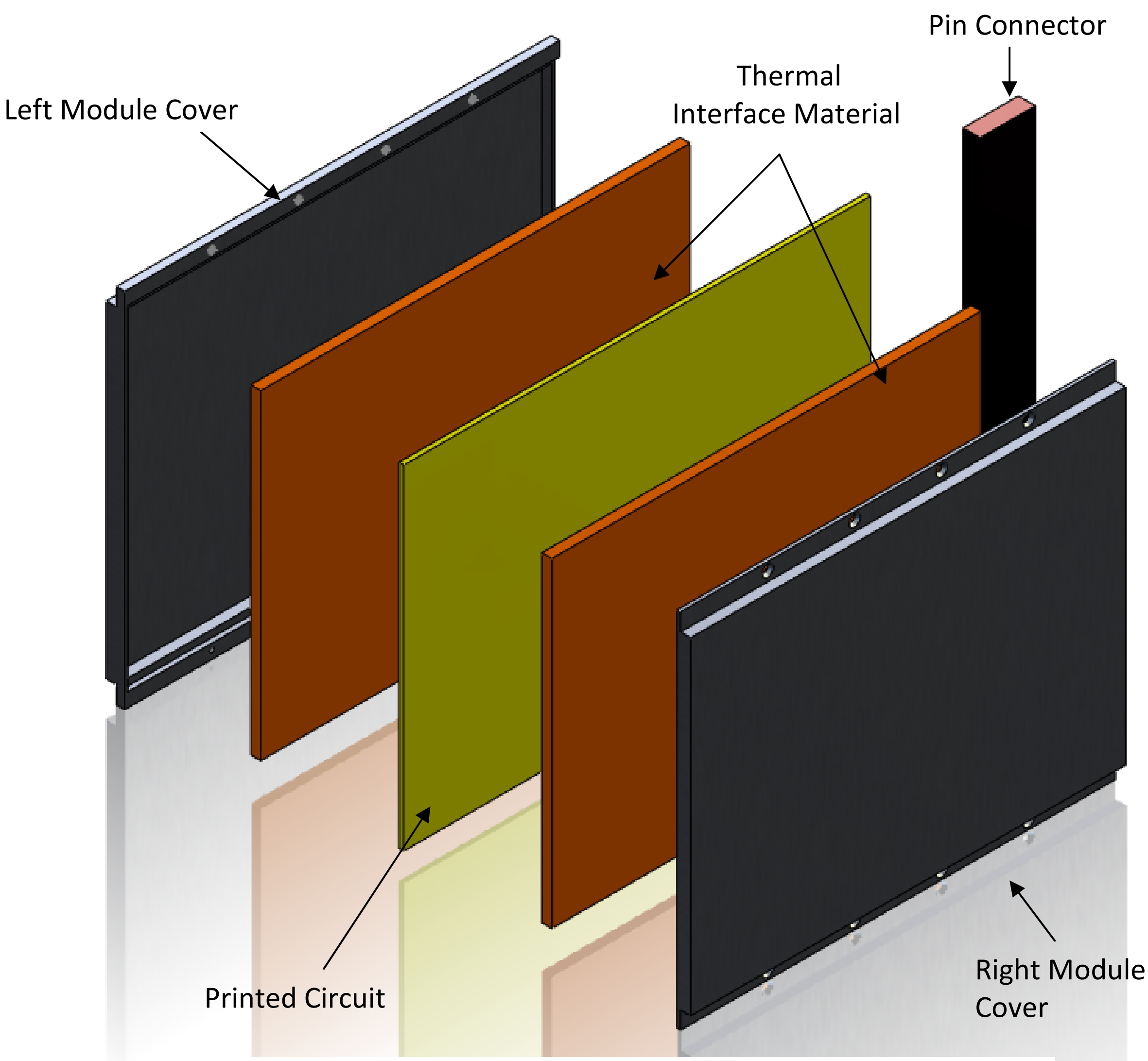


**Figure 13.** Exploded view of the second iteration AECM Module Cover for the Aluminum prototypes.

### *Module Covers (Left and Right)*

The left and right module covers completely encase the thermal interface material and all of the printed circuit board that is not encapsulated in the pin connector. The pin connector interacts with the printed circuit board and the pin interface at the rear of the cabinet. In our prototype the pin connector will be represented by an extension of the PCB. Through vibration analysis it was determined that no standoffs were needed to secure the printed circuit board within the case. The operating frequencies of the aircraft are not within the range of the harmonic frequency of the case.

### *Thermal Interface Material*

The interface material used will be Therm-A-Gap 579/580 and conduct heat from the heat generating components attached to the printed circuit board to the module case covers. Therm-A-Gap will be used during testing to conduct heat from the strip heaters to the module covers as well as cushion and dampen the vibrations of the PCB during testing.

### *Printed Circuit Board*

Blank PCBs were purchased for use in the prototype. Strip heaters supplied by Omega simulate the heat producing components mounted onto the PCB.

### *Pin Connector*

The pin connector allows the PCB to communicate with the main CPU aboard the aircraft. The design and testing of the pin connector however, is outside the scope of this project. Instead the PCB will be extended out.

### S-5.1b 6061 Final Module Cover Thermal Test Design

In order to properly test the thermal conductive properties of the 6061 aluminum, the final testing design must incorporate certain aspects. These aspects include using cork and electric strip heaters for testing. These will be inserted in between the module cover and the printed circuit board.

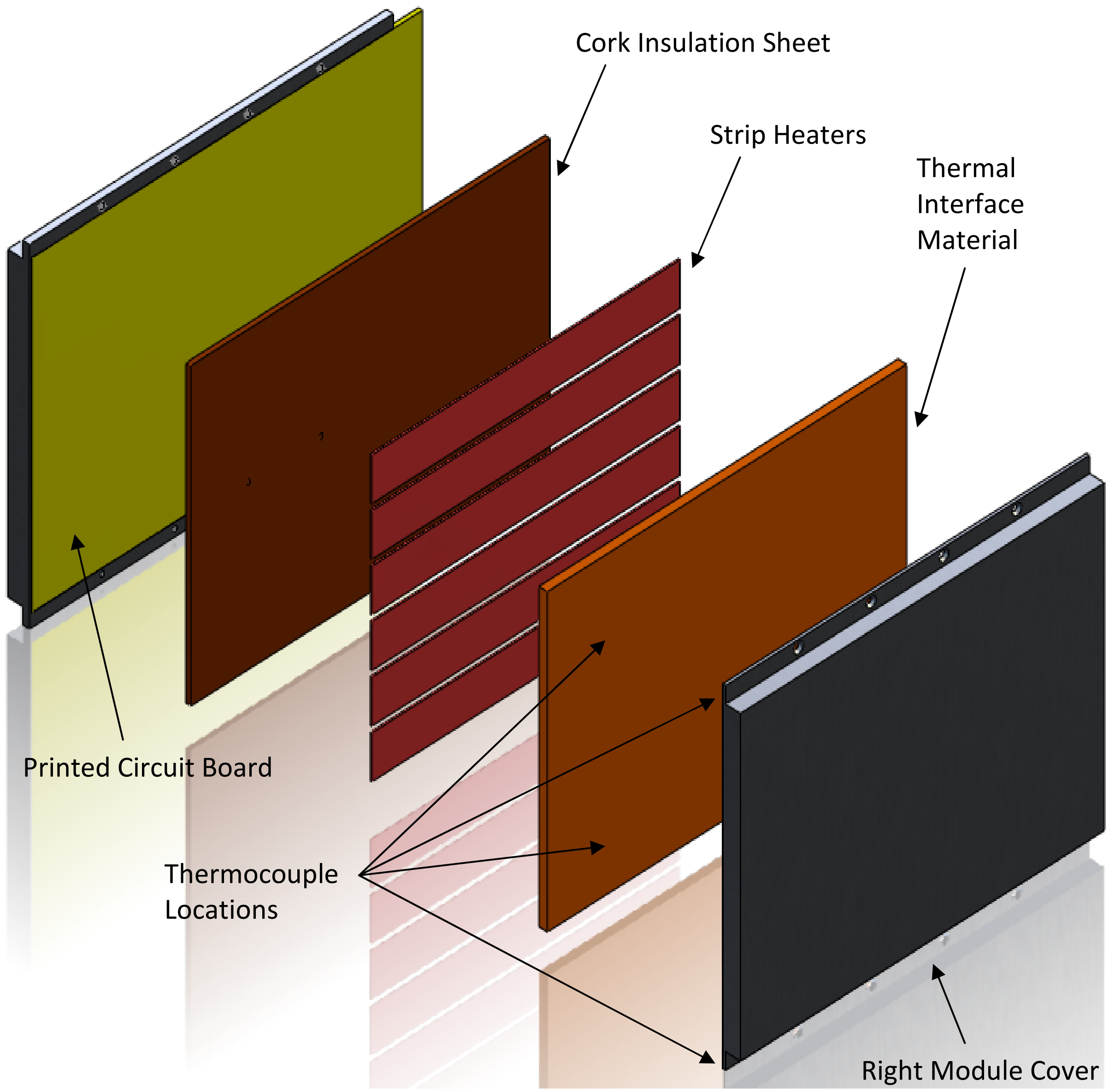


**Figure 14**. Exploded view of 6061 Aluminum test module cover design, including the cork sheet and strip heaters used for thermal testing.

### *Strip Heaters*

Strip heaters purchased from Omega will be used to simulate the heat producing components mounted on either side of the PCBs. A power source will be used to supply various voltages at incremental steps to determine the maximum wattage which can be achieved and maintain a PCB temperature below 105 degrees Celsius.

### *Cork Insulation Sheet*

The cork insulation sheet is used as a protective barrier, to shield the PCB against overheating during testing and to replicate the junction resistance between microprocessors and a PCB. The cork insulation will allow us to calculate the resistance of the cork by placing thermocouples on the outside of thermal interface material. After calculating this resistance, the appropriate wattage needed to replicate the junction temperature of 105ºC can be used without damaging the PCB.

### *Thermocouples*

Thermocouples will be purchased from Omega and used to measure temperature at multiple locations in our thermal test fixture. Locations include:

- On the outside of thermal interface material (module cover side)
- On the PCB to ensure the temperature does not exceed 105°C
- In the inlet and outlet of the cold plate coolant
- On the outer surface of the module cover

All thermocouples will be connected to a DAQ. Thermal tape will keep the thermocouple in position.

## S-5.2 Annealed Pyrolytic Graphite Module Cover

The Annealed Pyrolytic Graphite Module Cover design is very similar to that of the 6061, but has APG embedded within the walls of the module cover. Initially our contact was Mr. Montesano at k-Technology, which was the company that invented and patented the APG embedding process. Since the beginning of the project, k-Technology has been purchased by Thermacore Inc. During this time we lost contact with Mr. Montesano and an APG prototype (Appendix C-15 – C17) could not be manufactured in time to be tested for this report. However, Mr. Kusuda has recently contacted Thermacore and if an APG prototype is manufactured, testing of the prototype will occur at the discretion of Mr. Kusuda. The current design has specified an APG insert with a width of 0.035in. within the outer walls of the modules. The aluminum walls on either side of the APG will be approximately 0.020in. These specifications were suggested by Mr. Montesano in May 2009.

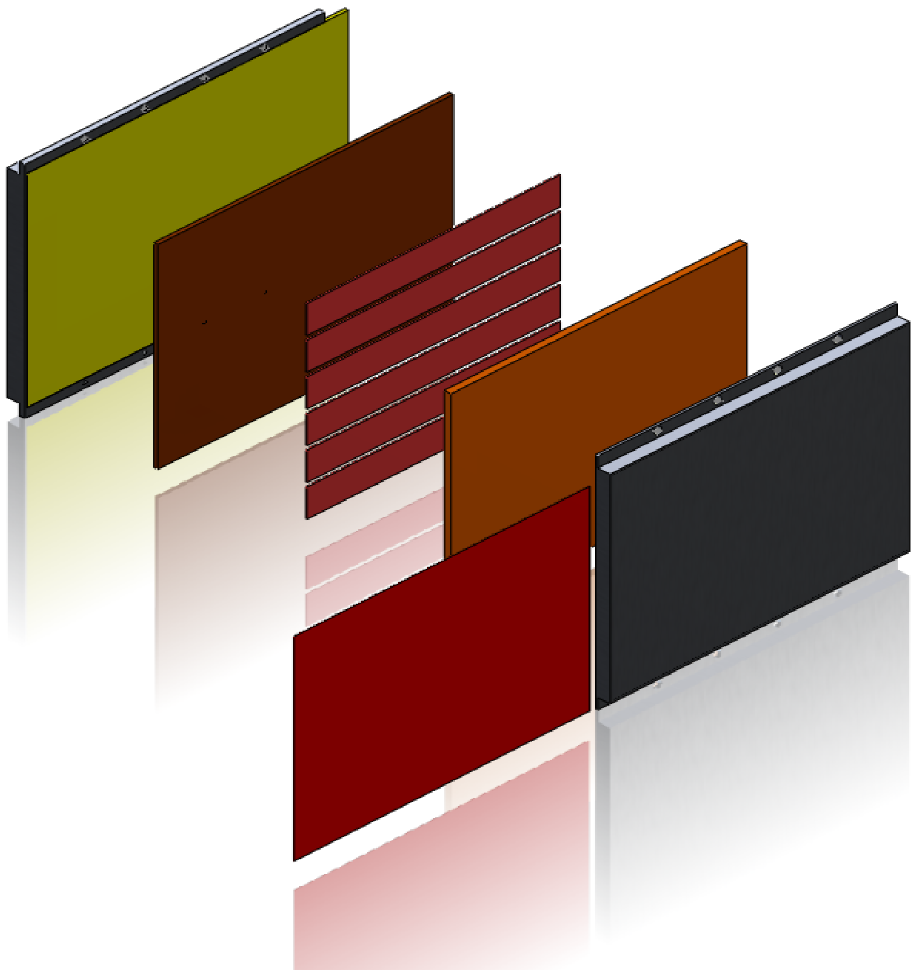

**Figure 15.** Exploded view of the first iteration of the Annealed Pyrolytic Graphite module cover

## S-5.3 Thermal Test Fixture

The final thermal test fixture design uses a cold plate with a serpentine channel through which cooling water is circulated in order to carry heat away from the module cover. The cold plate design was based upon the both the information provided by Mr. Kusuda as well as the cold plate design made by the cold plate development group.

### S-5.3a Hydraulic Diameter and Flowrate

In order to properly calculate the amount of heat transfer that the cold plates will be able to dissipate, the Reynolds Number and Nusselt Number for the flow the coolant through the cold plate is needed. With information provided by Charles Kusuda (Table 3) we used his Engineering Equation Solver (EES) model in order to estimate the velocity and flow rate of the serpentine channel. We assumed a hydraulic diameter of 0.375 in. in order to match the results obtained with the EES program. The serpentine channel of the cold plate uses square channel because of CNC manufacturing process used. In order to obtain an equivalent hydraulic diameter, or the equivalent diameter of a circular tube, the following equation was used:

$$D_h = \frac{2ab}{(a+b)}$$

a = width of channel
b = height of channel

$$D_h = \frac{2(0.375in)(0.375in)}{(0.375in + 0.375in)}$$

$$D_h = 0.375in$$

This calculation shows that the hydraulic diameter of 0.375in x 0.375in square channel has the same hydraulic diameter of a 0.375in circular tube. Therefore, the flow rate and velocity of the square channel of the cold plates should be equivalent to that of using a circular tube.

After the hydraulic diameter was calculated the, flow rate was calculated based upon the velocity and mass flow rate provided in the EES solution (Table 3).

**Table 3.** Result of EES analysis providing velocity and mass flow rates for varying diameter cooling channels

| D (in) | Re | T_chip (C) | T_in (C) | Number of Channels | u (m/s) | Z (lb/min/kW) | m_dot (kg/s) | m_dot (lb/min) | del_P (PSI) |
|---|---|---|---|---|---|---|---|---|---|
| 0.12 | 2725 | 80 | 60 | 24 | 0.4022 | 4.218 | 0.08799 | 11.64 | 0.03869 |
| 0.14 | 2655 | 80 | 60 | 24 | 0.338 | 4.827 | 0.1007 | 13.32 | 0.02363 |
| 0.16 | 2604 | 80 | 60 | 24 | 0.2916 | 5.439 | 0.1135 | 15.01 | 0.01548 |
| 0.18 | 2564 | 80 | 60 | 24 | 0.2564 | 6.053 | 0.1263 | 16.71 | 0.01069 |
| 0.2 | 2534 | 80 | 60 | 24 | 0.2288 | 6.669 | 0.1391 | 18.41 | 0.00769 |
| 0.22 | 2509 | 80 | 60 | 24 | 0.2065 | 7.286 | 0.152 | 20.11 | 0.00572 |
| 0.24 | 2489 | 80 | 60 | 24 | 0.1882 | 7.904 | 0.1649 | 21.81 | 0.00436 |
| 0.26 | 2472 | 80 | 60 | 24 | 0.1729 | 8.522 | 0.1778 | 23.52 | 0.00341 |
| 0.28 | 2457 | 80 | 60 | 24 | 0.1599 | 9.141 | 0.1907 | 25.23 | 0.00271 |
| 0.3 | 2445 | 80 | 60 | 24 | 0.1487 | 9.761 | 0.2036 | 26.94 | 0.00219 |
| 0.32 | 2434 | 80 | 60 | 24 | 0.139 | 10.38 | 0.2166 | 28.65 | 0.0018 |
| 0.34 | 2425 | 80 | 60 | 24 | 0.1305 | 11 | 0.2295 | 30.36 | 0.00149 |
| 0.36 | 2417 | 80 | 60 | 24 | 0.123 | 11.62 | 0.2424 | 32.07 | 0.00125 |
| 0.38 | 2409 | 80 | 60 | 24 | 0.1163 | 12.24 | 0.2554 | 33.79 | 0.00106 |
| 0.4 | 2402 | 80 | 60 | 24 | 0.1102 | 12.86 | 0.2683 | 35.5 | 0.00091 |
| 0.42 | 2397 | 80 | 60 | 24 | 0.1048 | 13.48 | 0.2813 | 37.21 | 0.00078 |
| 0.44 | 2391 | 80 | 60 | 24 | 0.09989 | 14.1 | 0.2942 | 38.93 | 0.00068 |
| 0.46 | 2386 | 80 | 60 | 24 | 0.09542 | 14.73 | 0.3072 | 40.64 | 0.00059 |
| 0.48 | 2382 | 80 | 60 | 24 | 0.09133 | 15.35 | 0.3202 | 42.36 | 0.00052 |
| 0.5 | 2378 | 80 | 60 | 24 | 0.08757 | 15.97 | 0.3331 | 44.07 | 0.00046 |

Based upon the velocity of the water the flow rate calculations were performed in order to give us a baseline flow rate at which to test. The flow rate was calculated in the following manner.

$$U = 0.1163\,\frac{m}{s} = 0.382\,\frac{ft}{s} \qquad A_{channel} = \left(\frac{0.375in}{12}\right)^2 = 9.76\ x\ 10^{-4} ft$$

$$Q = UA_{channel}$$

$$Q = (9.76\ x\ 10^{-4} ft)\left(0.382\,\frac{ft}{s}\right)\left(\frac{60s}{1\ min}\right) = 0.022357\ \frac{ft^3}{min}$$

$$Q = \left(0.022357\ \frac{ft^3}{min}\right)\left(\frac{7.48gal}{1ft^3}\right)$$

$$Q = 0.16723\ gpm$$

These results give an estimated flow rate for a coolant inlet temperature of 60°C. Using this estimated flow rate, the results of the cold plate testing should confirm that the cold plates can dissipate 240 watts of energy being input to the PCB. If the results vary, a justification of these results will be needed as well as recommendations for improving the test fixture and cold plate design.

### S-5.3b Cold Plate Manufacturing

Due to the complexity of the serpentine channel, the Mustang 60 machine shop was contacted to manufacture the cold plates. The cold plates were made with a Computer Numerically Controlled (CNC) mill. The original designs were given to the machine shop and a technician converted the SolidWorks into machine code so that the part could be milled. The serpentine channel has a height of 0.375in and a width of 0.375in. The cold plates are constructed from two separate pieces. The top plate (Figure 16) is made from a 1in thick plate of 6061 aluminum. Due to the fact that this is the thicker piece of material, the slot for the module cover and Birtcher clamp as well as the serpentine coolant channel are machined into this piece. The top half of the cold plate has a channel cut of 0.625in deep with a width of 0.375in. The top half of the cold plate also two 0.375in diameter tapped hole with 18 threads per inch. This hole accepts the 0.375in fittings for tubing in order to allow coolant to flow through the plate. The bottom half of the cold plate (Figure 17) has a mirror image of the serpentine channel but is raised 0.25 in off the surface of the plate. When the two pieces are joined, it allows for a tight fit and channel size of 0.375in by 0.375in. An exploded view of the cold plate can be seen in Figure 18 and a fully assembled test fixture can be seen in Figure 19.

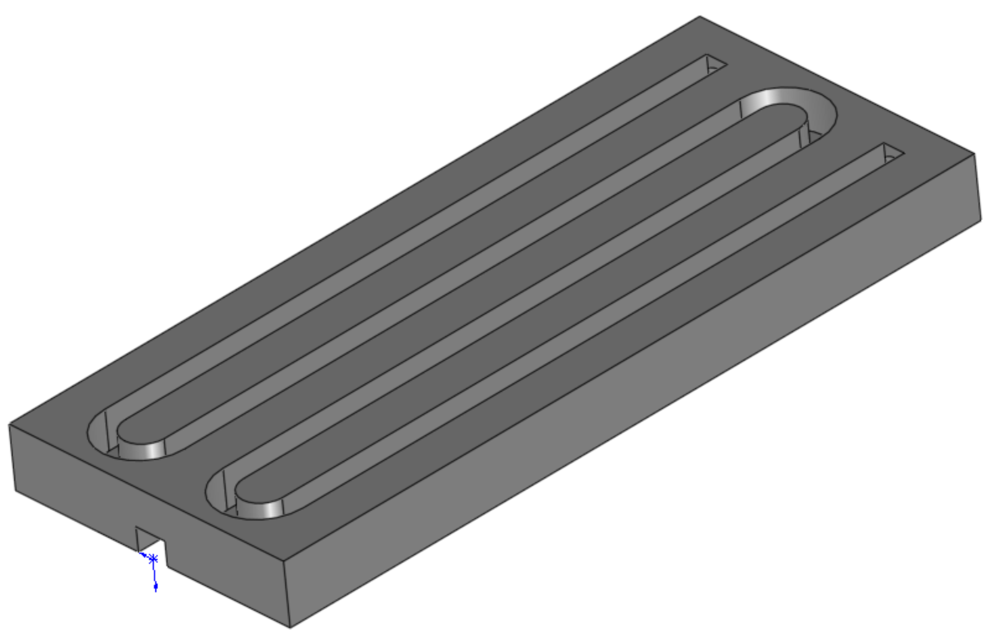

**Figure 16.** Isometric view of the top cold plate showing the serpentine channel.

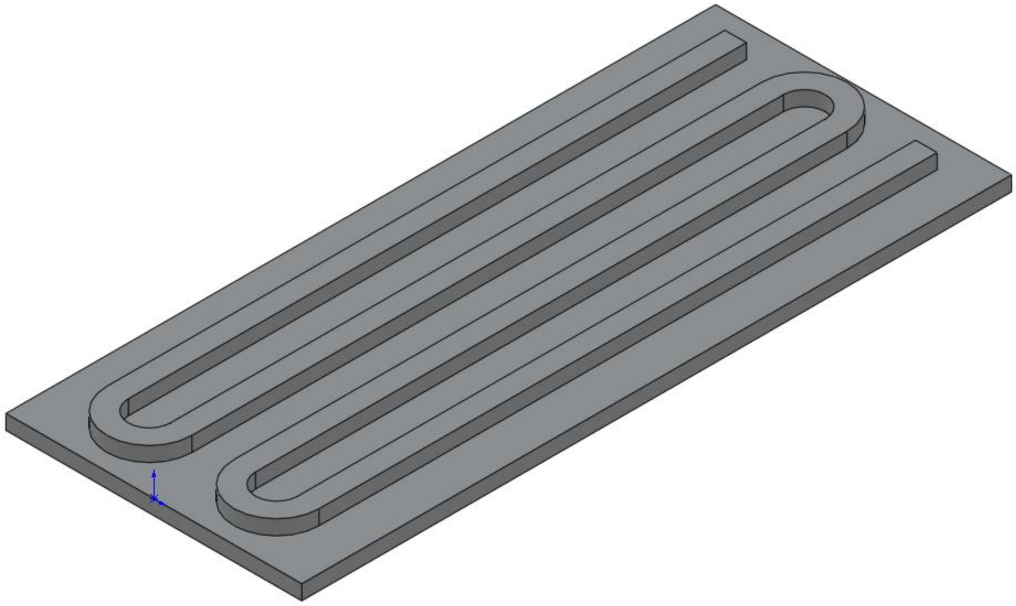

**Figure 17.** Isometric view of the bottom plate of the cold plate showing the raised mating serpentine ridge.

The cold plate channels were machined with 0.05in of clearance so that the raised bar of the bottom half could properly fit within the channel of the top half. There was a bit of an interference fit when assembling the cold plates but it wasn't enough to make a metal to metal seal of the plate. To solve this, silicone sealant as well as an instant gasket making material commonly used for automotive applications was used in order to for a liquid tight seal.

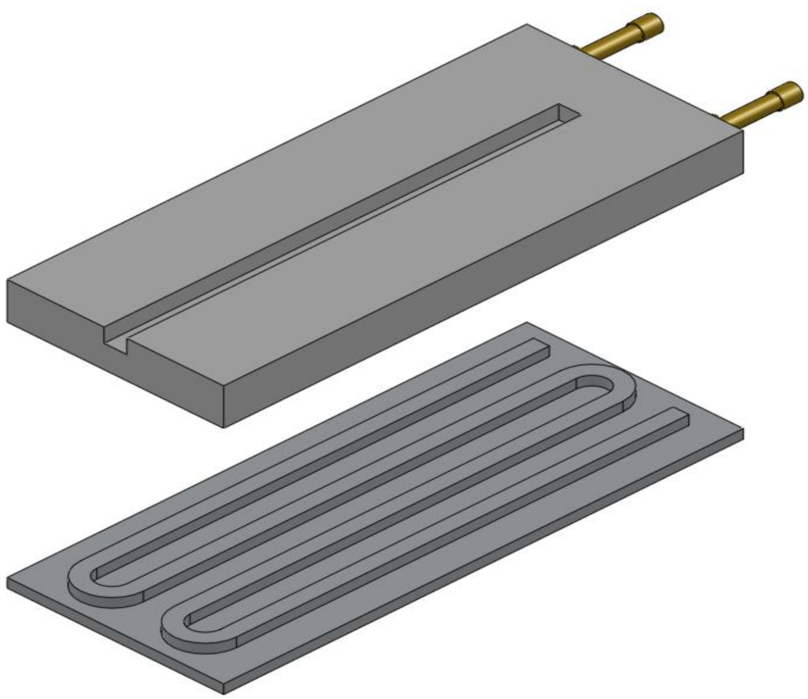

**Figure 18.** Exploded Isometric view of the cold plate including valves used for coolant flow.

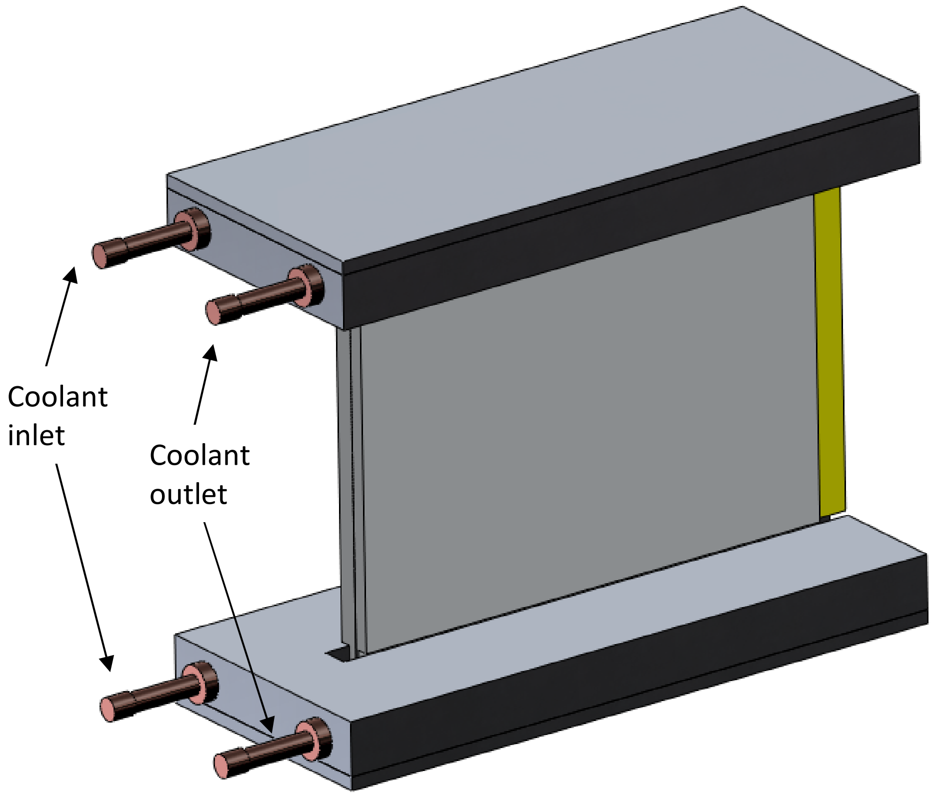


**Figure 19.** Isometric view of the assembled cold plates with the module cover inserted and clamped. (Note the module cover is insulated during testing to minimize convection)

### S-5.3c Fixture Incompatibilities and Solutions

**Proposed Test Fixture**

The thermal test fixture was built by the cold plate development group and was to be shared between the two groups. The system would use a flow regulator and a temperature control valve in order to regulate the flow and temperature of the coolant flowing through the cold plates. The exit water would flow through a heat exchanger and into a reservoir where it would be pumped back through the system. The temperature control valve would regulate the flow of this hot water and that of a cold water supply to acquire a desired temperature. The temperature at the inlet and outlet of the system was measured by thermocouples directly in the coolant flow. The valve would be adjusted according to the temperature data gained from the thermocouples.

**Incompatibilities**

Over the course of several days, the test fixture was used in conjunction with the cold plates seen in section S-5.3b. During the course of this testing several incompatibilities of the system were seen.

- **Garden Hose inlet** – The inlet connection made finding a water source close to a power source difficult because most garden hose spigots are outside away from easily accessible power sources.

- **Flowmeter** – The purchased flowmeter did not measure the flow rates being used because the lower limit of the flowmeter was approximately 1 gpm.
- **Valves** – The selected valves were supposed to be used to control the flow rate of both the hot and cold water sources were difficult to use and did not sufficiently regulate or stop the flow of coolant water even when fully closed.
- **No relief lines** – Not having relief lines led to an increase in the pressure lines when the flow rate was modified. This led to a concern of back pressure build up, which could potentially damage the pump when in use.
- **Oversized pump** – The pump had a significantly higher flow rate and amount of head than required. Due to the excess of head, the pressure of the coolant being forced through the cold plates caused continual leaks because the silicon sealant would rupture. The ruptures would cause small streams of water to leak from the plates as well as flow splitters. These streams would need to be covered in order to keep the electronics from coming into contact with water potentially causing a malfunction. Due to the leaks in the system, the cooling loop was no longer closed and the amount of return water was less than that of the pump flow rate. This in turn would cause the consistent filling of the hot side reservoir with water. The most abundant water source would be that of another water tap supplying cold water. Since the hot side reservoir would be used to achieve the desired water temperature of approximately 60˚C, it is not conducive to constantly mix the hot side reservoir water with a water supply of equal to or less than 20˚C.

**Solutions**

In order to complete testing, an alternative solution needed to be created. Instead of using the thermal test bench water supply a water faucet was used in its place. The alternative set up was deemed acceptable for the following reasons.

- **Variability of flow rate** – The faucet has an easily adjustable flowrate, which was measured by filling a reservoir over the course of a minute using the coolant outlet hose.
- **Constant temperature** – Using thermocouples to measure the inlet temperature of the coolant water over several runs shows that the water temperature remains relatively consistent at a temperature of approximately 52˚C.
- **Acceptable pressure** – The pressure of the faucet when set to the calculated flow rates as well as flow rates exceeding 1 gpm did not cause a catastrophic rupture of the silicon sealant.
- **Ease of setup** – Due to the fact that the faucet required only the movement our equipment a short distance as well as its close proximity to electrical outlets, the test setup was very conducive to setting up and tearing over the span of a few minutes. The test bench set up would have taken significantly more time to fine tune all three valves as well as moving the equipment a greater distance.

After weighting these options, the alternative test setup was chosen for testing. This test setup was used multiple times, each with consistent temperatures and similar results.

## S-5.4 Vibration Test Fixture

Due to time constraints to the project, Mr. Kusuda recommended that our report focus on the thermal testing and analysis of the project. However, the vibration test fixture and testing plan could be tested at a later time by a different team and their results could be compiled with this report. A point of interest would be the forces on the APG insert within the walls of the module cover as the case experiences deflections. Fatigue of the APG material may be a concern and may be examined in future tests. The reason vibration testing is required in order to measure the deflection of the case and printed circuit board under vibrations of varying frequencies. The module as a whole must pass the vibration test outlined in section S-5.3c. The test fixture (Figure 14) was designed to work with a vertical thrust shake table that is located in Cal Poly's vibrations lab.

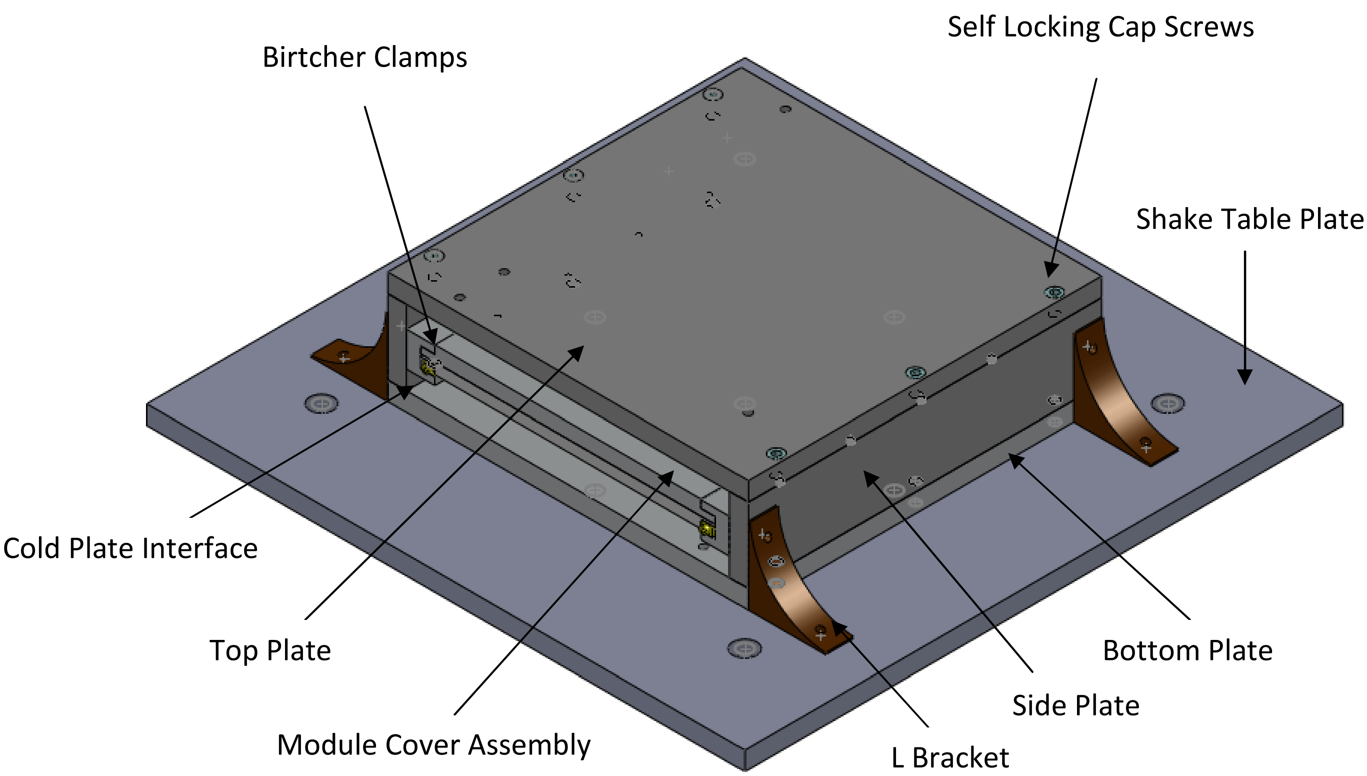


**Figure 20.** Isometric View of Vibration Test Fixture Assembly.

### *Top plate*

The top plate of the test fixture will have countersunk holes to attach the plate to the side plates of the test fixture. The self locking cap screws have a nylon patch and will use lock washers in order to keep the screws from vibrating loose and backing themselves out. (See Appendix C-11, AECMMC 3001)

### *Bottom plate*

The bottom plate will be almost identical to the top plate except that it will contain the threaded holes used for the clamping screws. (See Appendix C-12, AECMMC 3002)

### *Side Plates*

The side plates of the fixture will hold the entire fixture together. The side plates have threaded ¼ in holes so the self-locking cap screws from the top and bottom plate can thread directly into the plate and safely secure the top and bottom plate to the side plates. Lock washers will also be used on the threads of the cap screws to help keep the screws from loosening during testing. (See Appendix C-14, AECMMC 3004)

### *Shake table plate*

The shake table plate is a ½ in. aluminum plate drilled with countersunk threaded holes with the pattern of the shake table pillars. The shake table has threaded block pillars that rise up from the surface of the table. The idea behind this plate is to essentially provide a flat table that would allow us to apply anchor points where necessary to attach the rest of the fixture to it. (See Appendix C, AECMMC 3003)

### *Self Locking Cap Screws*

Self locking cap screws will be used in the test fixture to secure the top and bottom plates to the side plates as well as securing the L brackets to the shake table plate, and the shake table plate to the shake table, (Appendix C, 91205A565). Lock washers will be used on all threads in order to keep the screws from coming loose during vibration testing.

### *Self Locking Clamp Screws*

Self locking clamp screws will be inserted into the top plate of the test fixture and tightened to place force upon the block of the block of the clamping interface. (See Appendix C, 93705A628)

### *Accelerometer*

Accelerometers will be used to measure the response of the module cover as well as the PCB when subjected to vibrations of different frequencies. The Cal Poly Vibrations Lab also has accelerometers on hand, however if these are deemed unacceptable new accelerometers will be purchased. Minor adjustments to the module cover will be made to accommodate the accelerometer such as a nut mounted onto the surface to accept the threaded attachment. A hole will be cut into the cover and the Therm-A-Gap 579/580 so an accelerometer can be attached to the PCB itself. A hole will be cut into the vibration testing fixture itself as well to make room for the attached accelerometers.

# Section 6 - Manufacturing and Testing

## S-6.1 Manufacturing Plan (June 09)

**Machine aluminum 6061 covers >> 5/30/09 – 9/22/09**

- Work sporadically through-out summer quarter at machine shops at Cal Poly
- Have aluminum 6061 module cover finished by fall quarter (9/22/09)
- Contact Mustang 60 Machine shop to manufacture module cover

**Communicate with k-Technology and order APG module cover >> 5/11/09 – 9/22/09**

- Finalized drawings sent to k-Technology; awaiting estimated cost and delivery time
- Communication lost with k-Technology 5/2009
- Communication reestablished with Mr. Montesano and k-Technology (now Thermacore)
- Testing of APG module cover postponed and will be under the direction of Mr. Kusuda

**Thermal Test Bench >> 10/09 – 11/09**

- Design cold plates (10/15/09)
- Manufacturing of cold plates by Mustang 60 machine shop (10/16/09 – 10/20/09)
- Drilling and tapping of valve holes (10/20/09 – 10/28/09)
- Assembly of cold plates and preliminary testing at low pressures (10/28/09-11/6/09)
- Cold plate group thermal test fixture testing (11/12/09 – 11/20/09)
- Testing with alternative thermal test fixture (11/20/09 – 11/24/09)

**Machine Vibration Test Fixture and Electromagnetic Testing**

- Due to time constraints and the main object of the project to focus on the thermal capabilities of the module cover, these tests were postponed and not covered in this final report.

## S-6.2 Bill of Materials

The table below shows the final bill of materials for the project. It should be noted that costs that were not initially anticipated significantly contribute to the increase in price of the project.

**Table 4.** Bill of materials table summing the cost of the project.

| Bill of Materials | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Product** | | | | | | **Cost** | |
| **Name** | **Part Description** | **Supplier** | **Dimensions** | **Part Number** | **Quantity** | **Per Unit** | **Sub Total** |
| **Thermal Test Fixture** | | | | | | | |
| **Thermocouple** | Thermocouple | Omega | D= 0.032" | 5TC-GG-J-20-36 | 3 | $39 | $117 |
| **TC Adhesive Pads** | Thermocouple Adhesive | Omega | 5/8" x 1/2" | TAP | 1 | $28 | $28 |
| **Strip Heaters (Omega)** | Sample | Omega | 1" x 8" 10W per sq. inch | SRFG-108/5-P | 1 | $20 | $51 |
| **Strip Heaters (Omega)** | Heat Producer for PCB | Omega | 1" x 8" 10W per sq. inch | SRFG-108/5-P | 11 | $20 | $220 |
| **Insulation** | Cork Insulation | School Outfitters | 1/8" x 4' x 6' | N/A | 1 | $40 | $40 |
| **Aluminum 6061** | Cold Plate | McMaster Carr | 1" x 10" x 12" | 8975K103 | 1 | $58 | $58 |
| **Cold Plate Machining** | Cold Plate | Mustang 60 Machine Shop | N/A | N/A | 6.5 hrs | $16.5/hr | $107 |
| **Misc. Parts** | Home Depot | Home Depot | N/A | N/A | N/A | N/A | $200 |
| | | | | | | Subtotal | $821.33 |
| **Module Cover** | | | | | | | |
| **Aluminum 6061** | Cold Plate Interface | Aircraft Spruce | 6061 BAR 1" X 1" X 24" | 03-46450-2 | 1 | $3.90 | $7.80 |
| | Module Cover | McMaster Carr | 10" x1 2"x 0.75" Plate | 8975K122 | 4 | $47.61 | $190.44 |
| **Therm-A-Gap** | Thermal Interface Matl. | Parker | 18" x 18" x .040" | 69-11-20687-G579 | 2 | $92 | $1,146.83 |
| **Fasteners** | Cover | McMaster Carr | 1/8" Long Cap Screws | 91253A122 | 1pk (10) | $7.93 | $7.93 |
| **Printed Circuit Board** | PCB | Advanced Circuits | N/A | N/A | 2 | $17.90 | $35.80 |
| **Module Cover Machining** | Labor | Mustang 60 Machine Shop | N/A | N/A | 24 hrs | $16.5/hr | $396.00 |
| | | | | | | Subtotal | $1,784.80 |
| **Vibration Test Fixture** | | | | | | | |
| **Birtcher Clamps** | Birtcher Clamps | Bisco Industries | 7.5 in. long | 48-5s-15L | 2 | $60.99 | $0 (Given as Sample) |
| **Aluminum 6061** | Plates | McMaster Carr | 10" x1 2"x 0.5" Plate | 8975K107 | 4 | $30 | $120 |
| | Shake Table Plate | McMaster Carr | 18"x18"x0.5" Plate | 89155K29 | 1 | $136.24 | $136.24 |
| **Fasteners** | Brackets | McMaster Carr | 2 1/16"x2 1/16" | 1564A2 | 4 | $1.58 | $6.32 |
| | Test Fixture Bolts | McMaster Carr | 1/4"-28 L=1" | 91205A565 | 1 pk (25) | $0.45 | $11.26 |
| | | | | | | Subtotal | $273.82 |
| | | | | | | **Tax and Shipping** | $371.17 |
| | | | | | | **Project Total:** | $3,251.12 |

### *Increase in BOM Cost*

In the last report submitted, the BOM and budget of the project were not finalized. Unfortunately, several costs contributed to the increase in budget of $1083.89 (June 2009) to $3,251.12 (November 2009). The largest cost increase is due the purchase of the thermal interface material (Therm-A-Gap). This product was purchased through Parker Chromerics and was originally estimated to cost approximately $200 when in actuality it cost approximately $1200. The Therm-A-Gap material was shared between the module cover group and the convection cooling group. The cost of Therm-A-Gap material was placed on this budget because the cost of the purchased power supply (also used by both groups) was placed on the convection cooling group's budget. This was done in order to more accurately keep track of costs.

Another source of increased cost was the outsourcing of manufacturing of both the module covers and cold plates. The machining of module covers was scheduled to be done during the months of June – August, however, both members of the team were working 40 hours per week and due to the lack of availability to the machine shop, the decision was made to have the Mustang 60 machine shop machine the module covers. The cost of $396 was seen as a needed cost in order to stay on schedule with the module cover manufacturing plan. In October, after talking to the cold plate team and learning that the current cold plates manufactured by the team could not be used for testing, the need to design and fabricate new cold plates was realized. Due to the complexity of the serpentine channels, the use of a Computer Numerically Controlled (CNC) milling machine was needed. After designing new cold plates and gaining approval from Mr. Kusuda, the Mustang 60 machine shop was again contacted. The cost of machining the cold plate cost was $107, bringing the total cost of machining to $648.25. The balance cost of the budget was due to more needed material, such as 6061 aluminum for the cold plate ($58) and miscellaneous material needed for testing (approximately $200). The fees for tax and shipping were also significant and ended up being $371.17.

In conclusion, the budget increased a significant amount but the costs incurred were needed and the drastic under estimation of the Therm-A-Gap material was the biggest factor to the increase in the budget.

### *Annealed Pyrolytic Graphite Prototype Cost*

Due to the loss of communication between the group and k-Technology as well as the acquisition of k-Technology by Thermacore, the cost of the APG prototype will not be examined in this report. After talking to Mr. Kusuda, he suggested not including the cost of the APG prototype in the presented BOM and the prototype would not be paid for by the funds set aside for this project.

### S-6.3 Design Verification Plan and Report

NOTE: Testing with red text was neglected for this report in order to concentrate on the thermal testing of the module cover and cold plate at the suggestion of Mr. Kusuda.

**Table 5**. Projected testing plan for the module cover prototypes.

| TEST PLAN | | | | |
|---|---|---|---|---|
| **Item No** | **Specification or Clause Reference** | **Test Description** | **Acceptance Criteria** | **Test Responsibility** |
| 1 | Heat Transfer | Measure temperature at the interface between heat source and PCB | ≤ 105°C | Niles/Fort |
| 2 | | Measure temperature at the interface between heat source and the Therm-A-Gap | No regulation | Niles/Fort |
| 3 | EMC/EMI | Lightning induced EMI | Ample Shielding | Niles/Fort |
| 4 | Vibration | 5 hours of random noise | ≤ 4 Grms | Niles/Fort |
| 5 | | Free fall from 30 in | No damage to the PCB | Niles/Fort |
| 6 | Strength | Failure due to vibration induced deflection | No cracking | Niles/Fort |
| 7 | | Failure due to G-force induced deflection | No cracking | Niles/Fort |

***Heat Transfer***

This is the highest risk test since main requirement it to keep the PCB at or below 105 degrees Celsius. The coolant water will be maintained at a constant temperature when flowing into the cold plate in order to represent a typical heating scenario. Thermocouples attached to the inner wall of the module cover will provide temperature measurements in order to look at the heat distribution of the module cover and calculate the heat ratio traveling from the strip heaters to the circuit board and module cover. The desired wattage dissipation of the module cover is 239 Watts. During testing the wattage will be incrementally increased and the system will be allowed to reach steady state before another increase of wattage is performed. The group will try to reach a steady state condition of as close to the critical PCB temperature of 105˚C in order to measure the maximum amount of heat dissipation of the system.

***EMC/EMI***

The Cal Poly Electrical Engineering (EE) Department was contacted and we were referred to Professor Dean Arakaki for help in testing. Our education has not included much information about this topic and the EE Department would be a valuable resource. Due to this test being postponed, a fully detailed test plan must be formulated depending upon the resources available. If testing at Cal Poly is desired, Professor Arakaki would be the desired point of contact for information on electromagnetic testing.

### *Vibration*

The vibration testing of the module cover has been cancelled in order to fully pursue the thermal testing of the module cover and cold plates. However, prior to the decision to not pursue this testing, Cal Poly requested that the vibration test will be limited to the Preliminary Frequency Response Test outlined in the Equipment Vibration Test Requirements document. One test will be allotted for each module cover on its critical axis (when the cover is lying parallel to the vertical shake table). Future testing will be based upon the resources available.

### *Strength*

The module cover and PCB must be able to survive a 30 inch drop failing the material. The strength testing of this project has also been cancelled due to the module not being able to be fastened at the rails. The use of fasteners was not used in order to increase the surface area and ensure full contact between the module cover rails and the cold plate interface since the machine shop on campus was unable to counter sink at the required 82°.

### S-6.3a Testing Schedule

Thermal testing >> 10/20 – 10/25

- Test aluminum 6061 module cover as soon as possible
- Test module covers 3 times for consistency
- Test module at desire flow rate of 0.2 gpm
- Vary flow rates and measure system at steady state in order to establish maximum amount of energy dissipation.

Vibration testing >> 10/8 – 10/27

- Test aluminum 6061 and APG module with modified vibration test
    - "modified test" includes the Preliminary Frequency Response Test outlined in the Equipment Vibration Test Requirements document. One test for each module cover on the critical axis (when the cover is laying parallel to the vertical shake table)

Electromagnetic Compatibility testing >> 10/12 – 10/22

- Test aluminum 6061 and APG module for high frequency electromagnetic shielding capabilities.
    - High frequency pulses cause electrical components, especially PCBs, in close proximity to "couple" signals together causing potentially harmful interference

Strength testing >> 11/2

- Strength testing requires the module cover to survive a 30 inch drop without failure. If time permits a second vibration test may be conducted and results will be compared to those previous to the drop.

NOTE: Testing has been cancelled in order to focus effort on thermal testing of module cover and cold plates.

# Section 7 - MANAGEMENT PLAN

The project has been organized into three phases: research and analysis, prototype fabrication, and prototype testing and comparison.

## S-7.1 Research and Analysis Phase (January 2009-March 2009)

During the research and analysis phase, multiple materials for the module cover were researched. The cost and material properties of these materials were compared to that of 6061 aluminum, which was the original material suggested by Boeing for the module cover. After this phase of the project, aluminum encased APG, aluminum 3003, and aluminum 6061-T6 were selected. The fabrication of the APG and 3003 modules were not pursued because cost and a breakdown of communication between the group and k-Technology (now Thermacore) who was going to fabricate an APG based upon the developed design presented in Appendix C.

Originally, the team planned on using computer aided analysis to estimate the results of all three designs. With the intended production of only one module cover (6061 aluminum), the focus of the project changed. The focus turned to fabricating the module cover and comparing test results to those projections provided by Boeing.

Creating a BOM with the materials needed for fabrication and testing became the priority during the last half of the quarter. The goal was to create a complete BOM in order to order and procure parts as soon as possible in order to start the fabrication process early in April. Some of the items included in the BOM were 6061 aluminum, strip heaters, and thermocouples for measuring.

## S-7.2 Prototype Fabrication Phase (April 2009 – June 2009)

Once parts and materials have been obtained, the module covers can begin to be fabricated. Methods used for producing the module covers included CNC machining and outsourcing of the APG module to k-Technology (Now Thermacore). Further research and future collaboration with these departments will be pursued at the appropriate time. Some initial testing was planned in order to make sure the modules interacted correctly with the thermal test fixture and vibrations test fixture before the manufacturing and testing review (9/28/09). Due to setbacks, neither the thermal or vibration fixture were constructed at the time of the manufacturing and testing review. During the prototype fabrication phase, we were directed to work with the cold plate group and use the prototype they were planning on fabricating.

## S-7.3 Prototype Testing and Comparison Phase (Sept. 2009 – December 2009)

During the prototype testing and comparison phase, multiple tests of the 6061 aluminum module for thermal conductivity were planned. The vibration and electromagnetic testing were cancelled in an effort to concentrate efforts on the thermal testing and analysis.

Empirical data will be compared to the theoretical calculations and the module will be analyzed using the junction resistance values provided by Boeing. After all tests are completed and compared, recommendations will be made to Mr. Kusuda. A rough timeline has been developed and attached with specific tasks and dates.

Notable dates include:

| | | |
|---|---|---|
| April 20, 2009 | -- | Critical Design Review Week |
| June 1, 2009 | -- | Sponsor Update |
| June 1, 2009 | -- | Project Update Presentation – Procurement and Manufacturing Status |
| November 25, 2009 | -- | 3rd Boeing Deliverable |
| December 3, 2009 | -- | Senior Design Exposition |

Our testing dates were pushed back significantly because of delays in receiving the Therm-A-Gap material along with the need to design and fabricate a new cold plate system as well as troubleshooting the original thermal test bench design. The Therm-A-Gap material did not arrive until the end of October despite being ordered in August.

# Section 8 – Results and Conclusion

## S-8.1 Results

Table 6. Empirical data gathered from the testing of the module cover and cold plate system.

| | Uninsulated hot | | | | Uninsulated cold | Insulated hot | Insulated cold | Uninsulated cover |
|---|---|---|---|---|---|---|---|---|
| Flow Rate (oz/min) | 192 | 330 | 132 | 80 | 130 | 130 | 132,00 | 24,00 |
| Power in (W) | 139 | 139 | 150 | 139 | 217 | 218 | 138,00 | 138,00 |
| Temp in (°C) | 49,1 | 50,44 | 52,9 | 57,3 | 18,63 | 18,5 | 52,10 | 0,00 |
| Temp out (°C) | 50,3 | 49,75 | 50,7 | 54,1 | 19,54 | 19,40 | 50,20 | 0,00 |
| PCB temp (°C) | 101,2 | 102,8 | 103,6 | 102,6 | 102,3 | 102,3 | 102,20 | 102,00 |
| 1 | 69,9 | 71,08 | 67,12 | 70,8 | 51,97 | 51,9 | 68,10 | 70,40 |
| 2 | 73,95 | 73,37 | 71,2 | 73,7 | 55,72 | 54,7 | 72,60 | 74,20 |
| 3 | 64,15 | 65,12 | 62,5 | 66,5 | 42,59 | 41,2 | 63,50 | 63,80 |
| 4 | 74,03 | 75,23 | 72,9 | 76,2 | 56,67 | 56,6 | 73,90 | 72,80 |
| 5 | 65,37 | 66,06 | 65,4 | 69 | 43,12 | 42,8 | 65,70 | 65,30 |
| 6 | 70,68 | 71,65 | 71,2 | 74,4 | 51,33 | 51,1 | 70,90 | 69,70 |
| 7 | 63,93 | 64,8 | 64,4 | 68,1 | 42,26 | 42,1 | 64,70 | 62,60 |
| 24 | 60,25 | 60,7 | 58,8 | 63,5 | 33,37 | 33,4 | 59,30 | 62,50 |
| 25 | 72,45 | 73,1 | 70,7 | 74,8 | 50,13 | 50,3 | 70,80 | 74,30 |
| 26 | 68,94 | 69,52 | 66,1 | 70,8 | 43,35 | 43,5 | 66,80 | 70,20 |
| 27 | 71,12 | 71,7 | 70,5 | 74,2 | 50,55 | 50,6 | 70,40 | 71,00 |
| 28 | 59,8 | 60,14 | 60,62 | 64,9 | 35,44 | 35,4 | 60,40 | 59,90 |
| 29 | 71,87 | 72,4 | 73,5 | 77,2 | 54,1 | 54,2 | 72,70 | 71,40 |
| 30 | 66,05 | 66,34 | 67,7 | 71,9 | 45,8 | 45,8 | 67,6 | 65,70 |
| Tsh | | | 87,7 | | | | 87,70 | 86,00 |
| Tout | | | 64 | | | | 64,00 | 53,00 |

Note: The columns in red are comparable since they were tested at the same flow rate. Tsh is the temperature at the strip heaters. Tout is the temperature on the outside wall of the module cover. ‘Temp in’ and ‘Temp out’ are measured at the inlet and outlet (respectively) of the cold plate.

Table 7. Conversion from oz/min to GPM

| Flow Rate | |
|---|---|
| oz/min | GPM |
| 192,00 | 1,50 |
| 330,00 | 2,58 |
| 132,00 | 1,03 |
| 80,00 | 0,63 |
| 130,00 | 1,02 |
| 24,00 | 0,19 |

## S-8.2 Calculations

Calculating aluminum resistivity ($R_A$) and interface material resistivity ($R_i$)

$$R_A = \frac{L}{kA}$$

$$R_A = \frac{(.201in)\left(\frac{1m}{39.37in}\right)}{\left(167\frac{W}{mK}\right)(64.4in^2)\left(\frac{1m^2}{39.37^2in^2}\right)}$$

$$R_A = .00073\frac{K}{W}$$

$$R_i = \frac{L}{kA}$$

$$R_i =. \frac{.0005}{\left(3\frac{W}{mK}\right)(64.4in^2)\left(\frac{1m^2}{39.37^2in^2}\right)}$$

$$R_i = .004\frac{K}{W}$$

*k Value according to Chromerics

Calculating cork resistivity ($R_c$)

$$q_{in} = q_{PCB} + q_i + q_A$$

$$q_{in} = \frac{T_{sh} - T_{PCB}}{R_c} + \frac{T_{sh} - T_A}{R_i} + \frac{T_A - T_{out}}{R_A}$$

$$\frac{T_{sh} - T_{PCB}}{R_c} = q_{in} - \frac{T_{sh} - T_A}{R_i} - \frac{T_A - T_{out}}{R_A}$$

$$R_c = \frac{T_{sh} - T_{PCB}}{q_{in} - \frac{T_{sh} - T_A}{R_i} - \frac{T_A - T_{out}}{R_A}}$$

$$R_c = \frac{360.7K - 375.2K}{69W - \frac{360.7K - 343.4K}{.004\frac{K}{W}} - \frac{343.4K - 337K}{.00073\frac{K}{W}}}$$

$$R_c = .00111\frac{K}{W}$$

(Values used the insulated hot test at ~1 GPM)

Notes: Calculated value of $R_c$ is inconclusive since it is less than $R_i$. The $R_{j\text{-}b}/R_{j\text{-}c}$ (junction to board/junction to cover) ratio presented by Boeing was 0.0167, while the $R_{j\text{-}b}/R_{j\text{-}c}$ using empirical data is 2.19 ($R_i/(R_c+R_A)$).

Calculating the ratio of heat flux through the module cover between the prototype and theoretical model

$$\frac{q_t}{q_a} = \frac{\frac{k * A_t}{l} * (T_1 - T_2)}{\frac{k * A_a}{l} * (T_1 - T_2)}$$

$$\frac{q_t}{q_a} = \frac{A_t}{A_a}$$

$$\frac{q_t}{q_a} = \frac{9.45 * .201}{9.45 * .075} = 2.68$$

The prototype can theoretically sustain 268% more heat flux than the theoretical module since the cross-sectional area of the prototype ($A_t$) is so much larger than the theoretical cross-sectional area ($A_a$). However, during the testing it seems that the majority of the heat never makes it to the module cover and therefore this increase in thermal capability is not taken advantage of.

## S-8.3 Conclusions

Results from testing show that the prototype can only dissipate about 57.7% of the wattage calculated in the theoretical model. The temperature of the module cover shown in Figure 3 never drops below 90°C. Contrarily, the temperature of the prototype module cover never exceeded 77.2°C. Some of this discrepancy is due to the temperature of the coolant (80°C vs ~53°C), however such an increase in the temperature gradient should translate to a substantial increase in the wattage dissipation of the prototype. The heat generated by the strip heaters seems to be prevented from conducting out to the module cover and through to the cold plates. It is possible that the thermocouple array is creating air pockets between the module cover and Therm-A-Gap, acting as an insulator instead of a conductor as anticipated. The temperature *drop* between the coolant inlet and coolant outlet suggests that energy is added to the system through the cold plates. Another possible explanation for the temperature drop between the coolant inlet and outlet is convection from the cold plate to ambient air; despite the cork insulation (which from the empirical data *conducts* heat better than the Therm-A-Gap). We believe that there are errors in the experimental setup because cork should insulate rather conduct. In order to obtain more accurate test results in the future, a list of recommendations has been created by the team.

## S-8.4 Recommendations

Future iterations should include experimentally determining the thermal resistivity of the cork and Therm-A-Gap rather than relying on distributer specifications. Including a thermocouple array between each layer would provide more insight to the heat flux as it flows through the system, but the creation of air gaps must be accounted for. Using actual microprocessors as the heat source on the PCB would also be desirable since it better represents the actual system and eliminates potential discrepancies with the strip heaters.

Changes to the cooling loop would include a system which provides water at 80°C at variable flow rates which include rates lower than 1 GPM. Testing the cold plates separately to insure they can handle 239 watts directly would allow for the assumption that any wattage dissipation lower than 239 must be due to the thermal properties of the module itself.

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# Appendix A-1 – Module Cover Dimension Overview

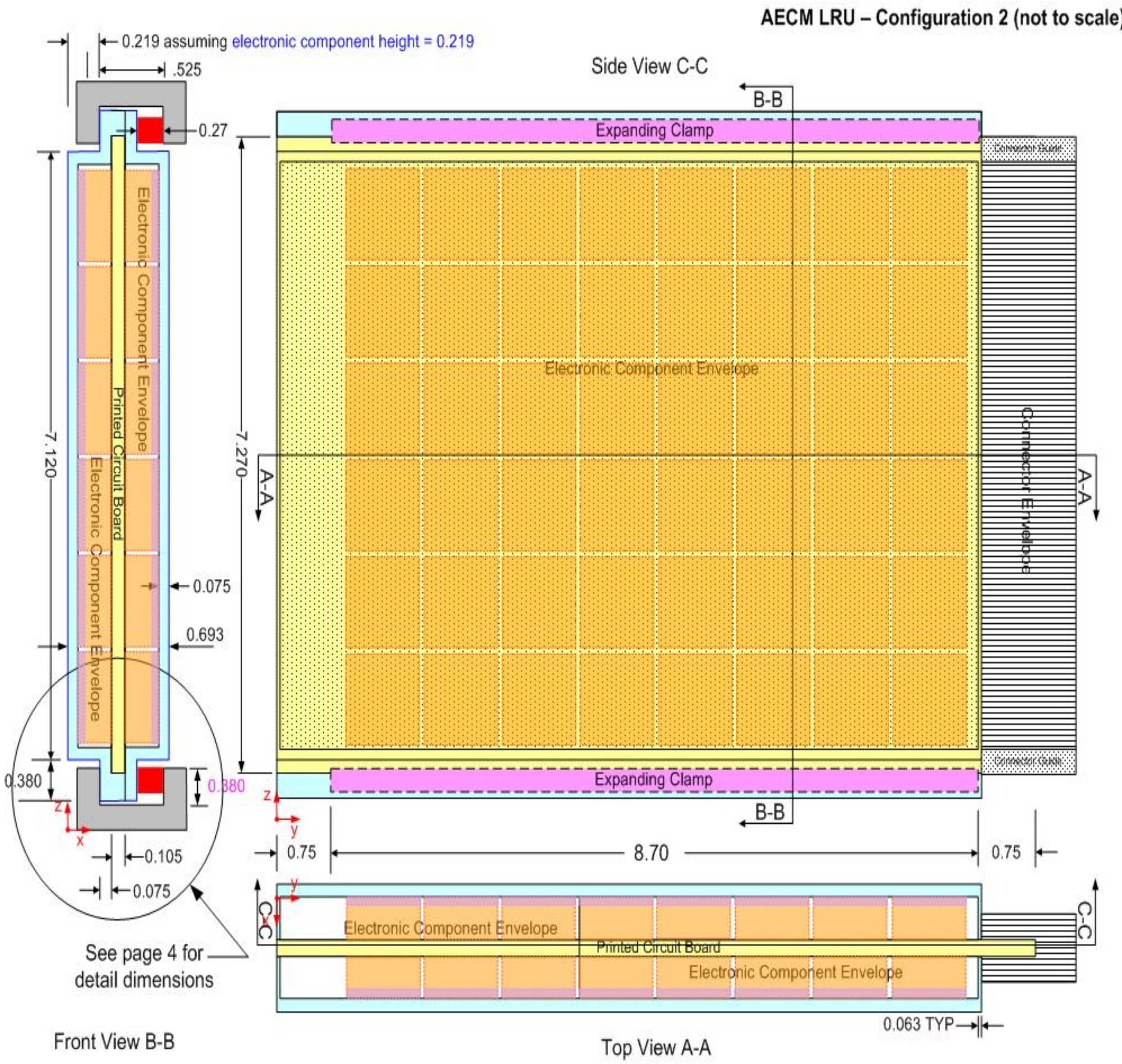



**Figure A-1.** Dimensions of the AECM Configuration 2 design provided by Boeing.

## Appendix A-2 – (End View – 3 Adjacent Module Covers)

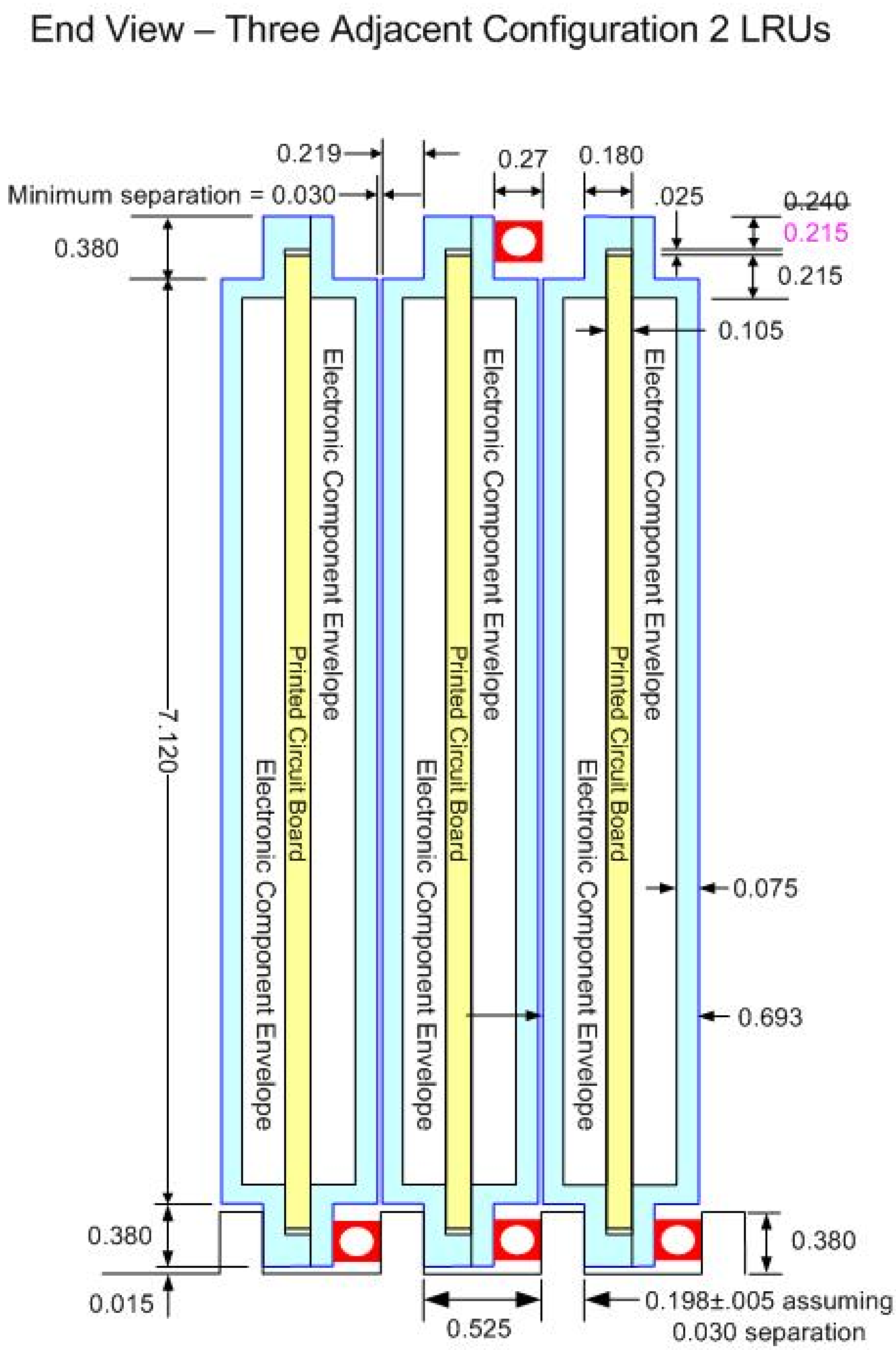



**Figure A- 2.** Size and dimensions of AECM configuration 2 module cover.

# Appendix B – Thermal Images

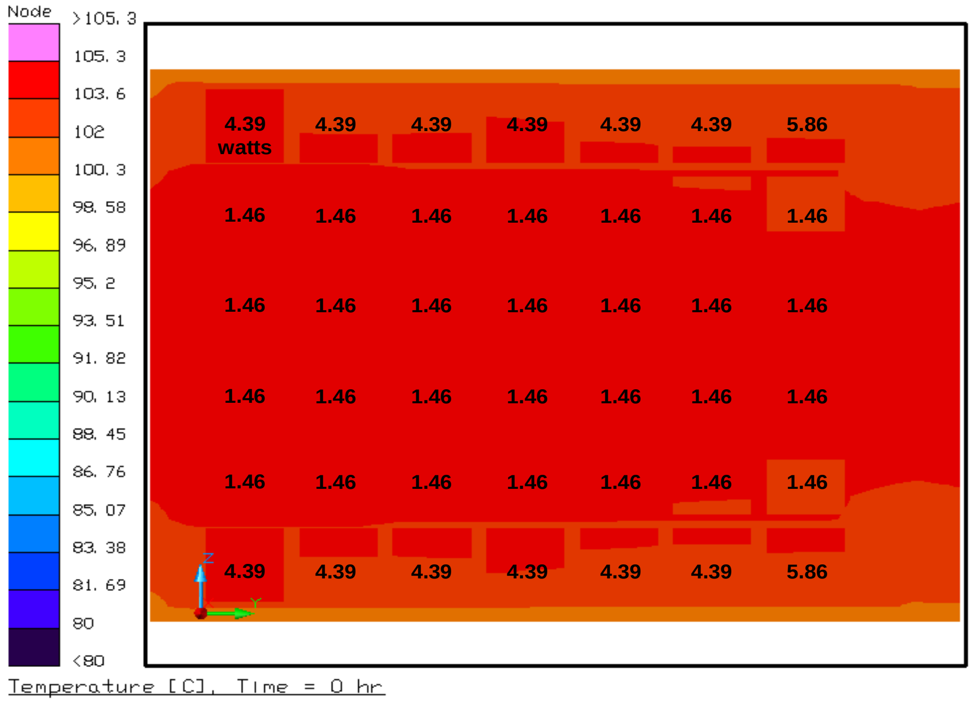



**Figure B-1.** Predicted AECM circuit board and component temperatures (C) with heat dissipation (W) (right side)

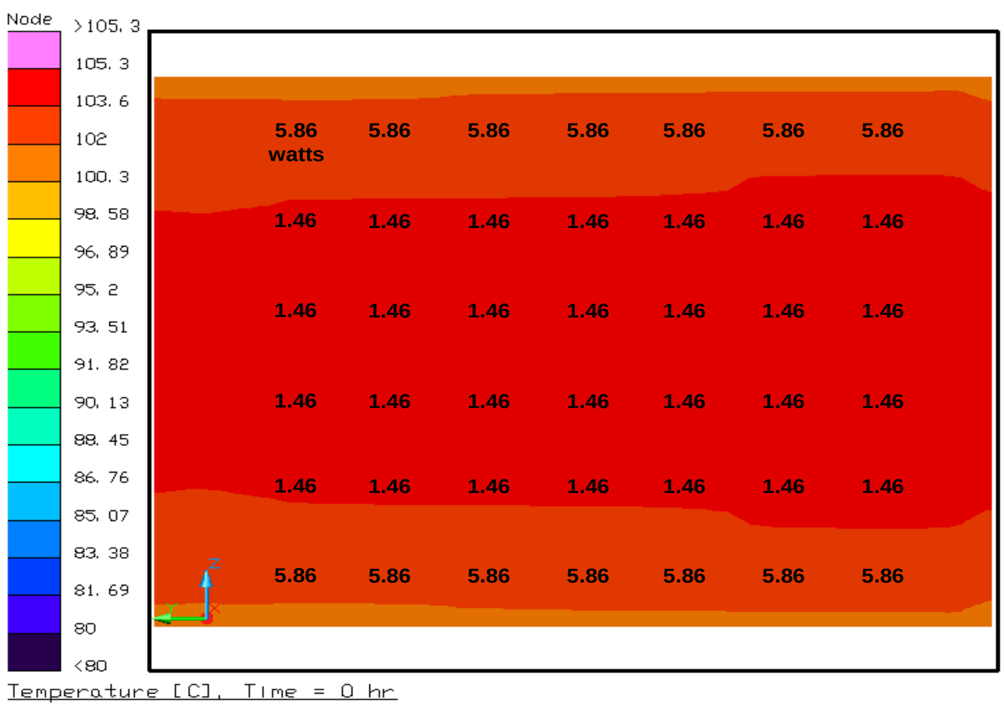



**Figure B-2.** Predicted AECM circuit board and component temperatures (C) with heat dissipation (W) (left side)

# Appendix C – Engineering Drawings

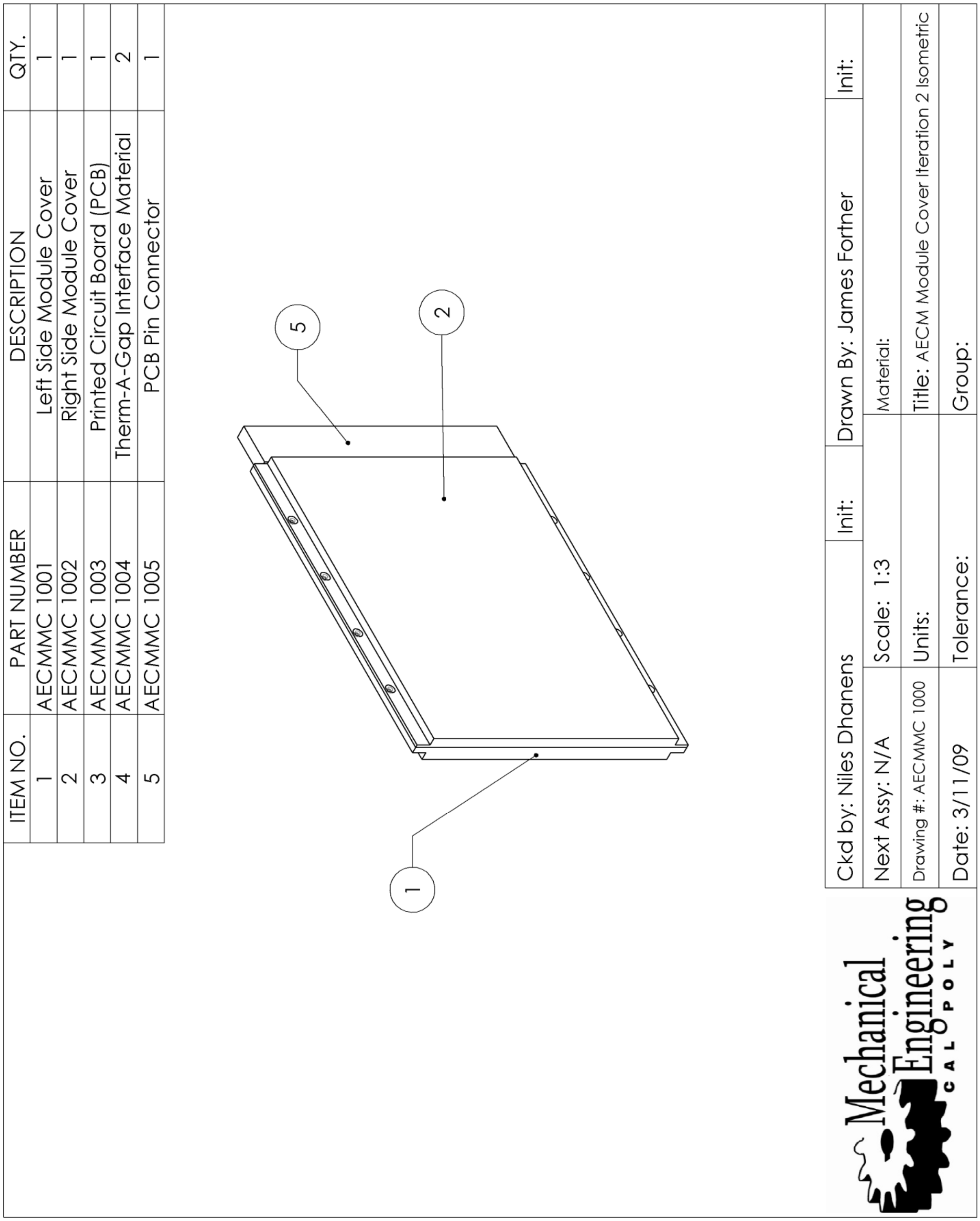
## List of Drawings

### Final Concepts

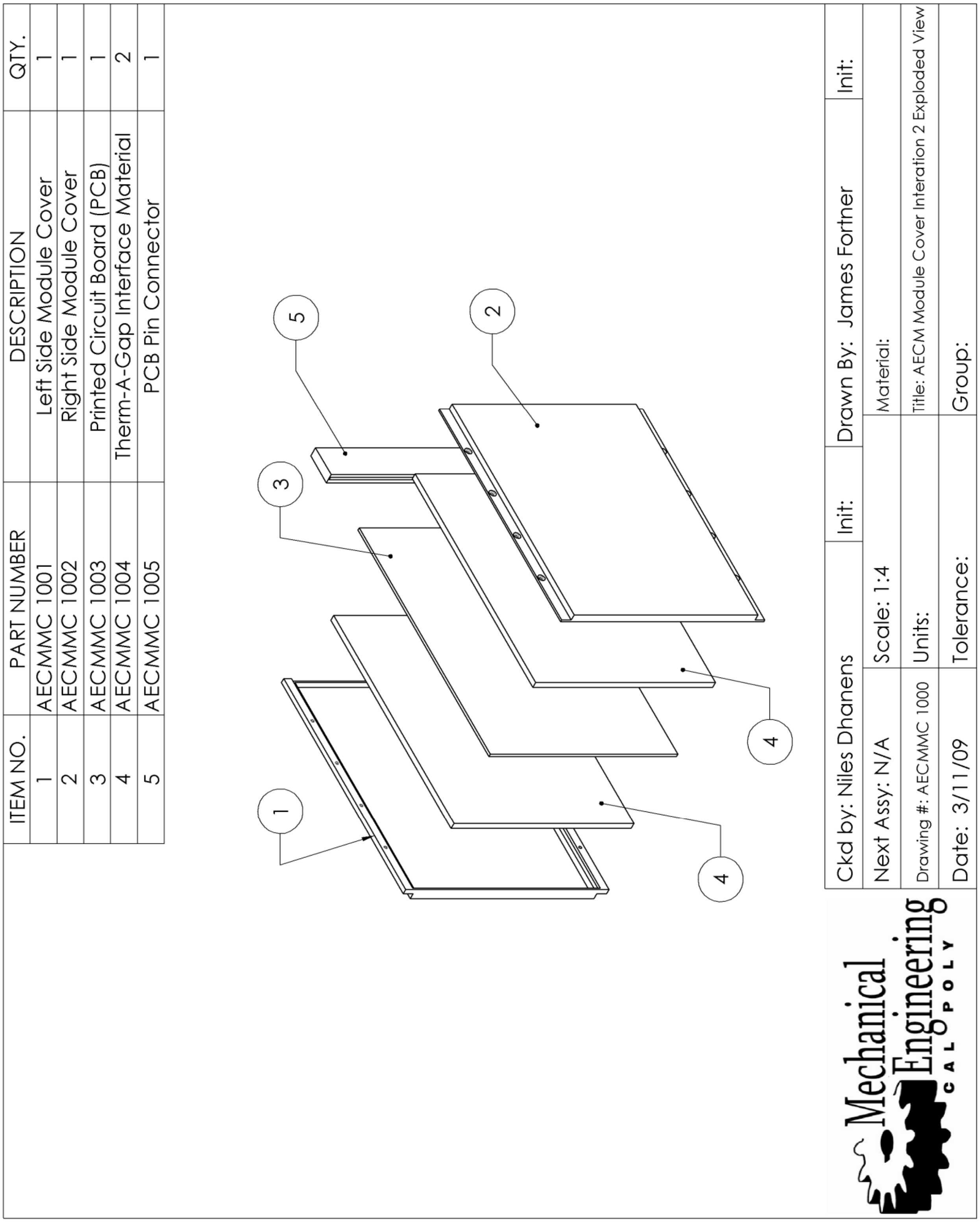


### Initial Concepts

## Appendix C-1 – (AECMMC 1000-Module Cover Assembly View)

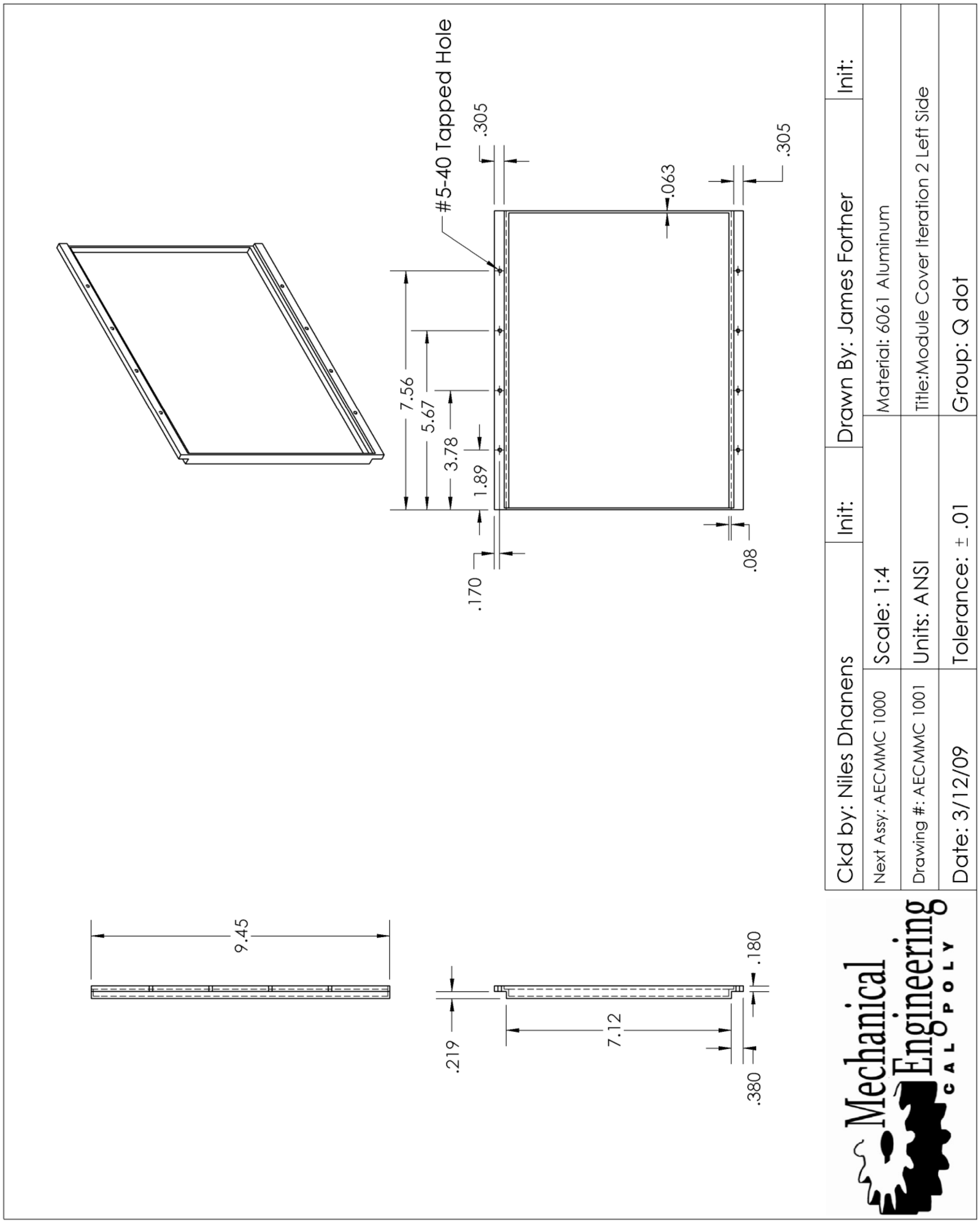


# Appendix C-2 – (AECMMC 1000 – Module Cover Assem. Exploded View)

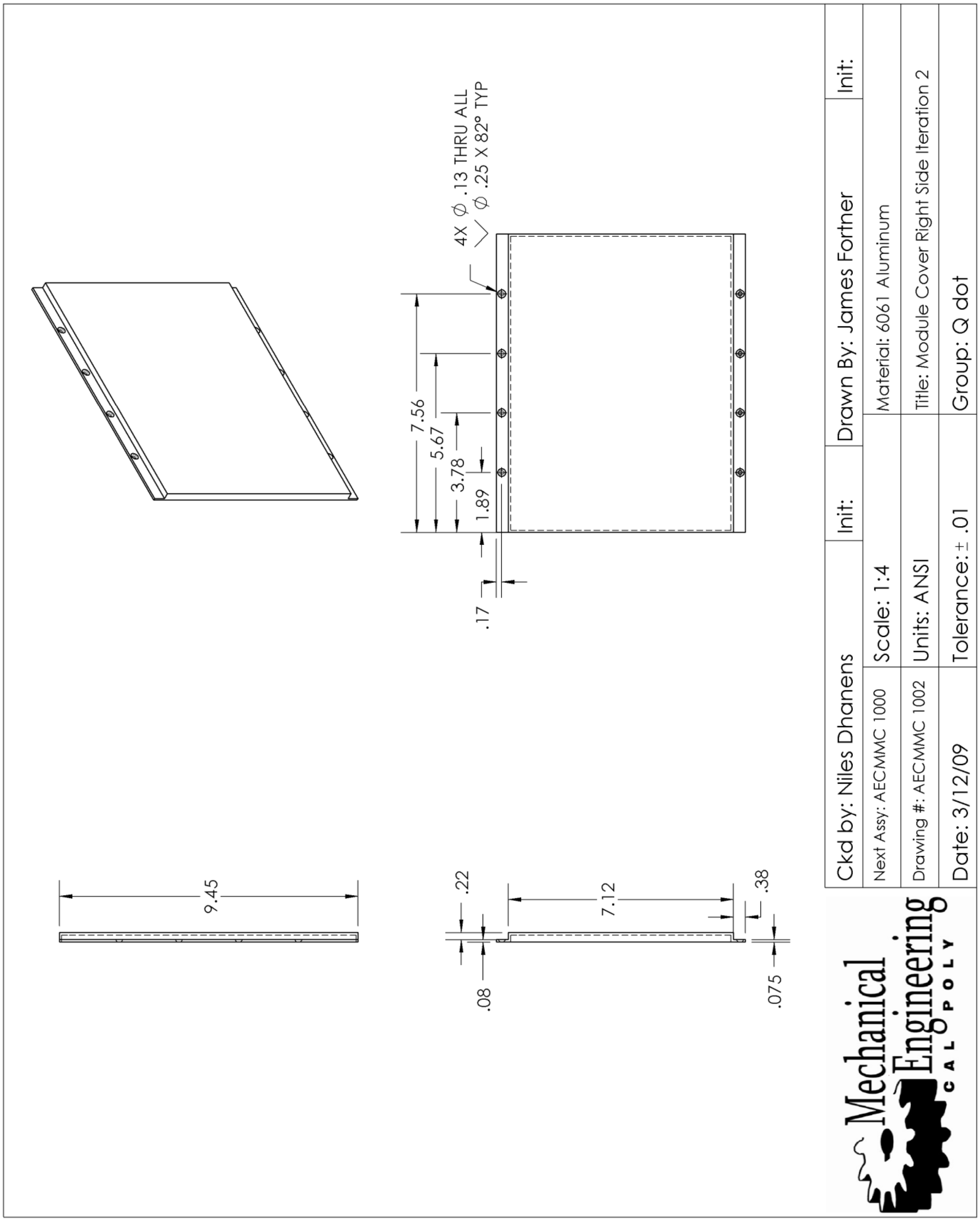



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
| --- | --- | --- | --- |
| 1 | AECMMC 1001 | Left Side Module Cover | 1 |
| 2 | AECMMC 1002 | Right Side Module Cover | 1 |
| 3 | AECMMC 1003 | Printed Circuit Board (PCB) | 1 |
| 4 | AECMMC 1004 | Therm-A-Gap Interface Material | 2 |
| 5 | AECMMC 1005 | PCB Pin Connector | 1 |

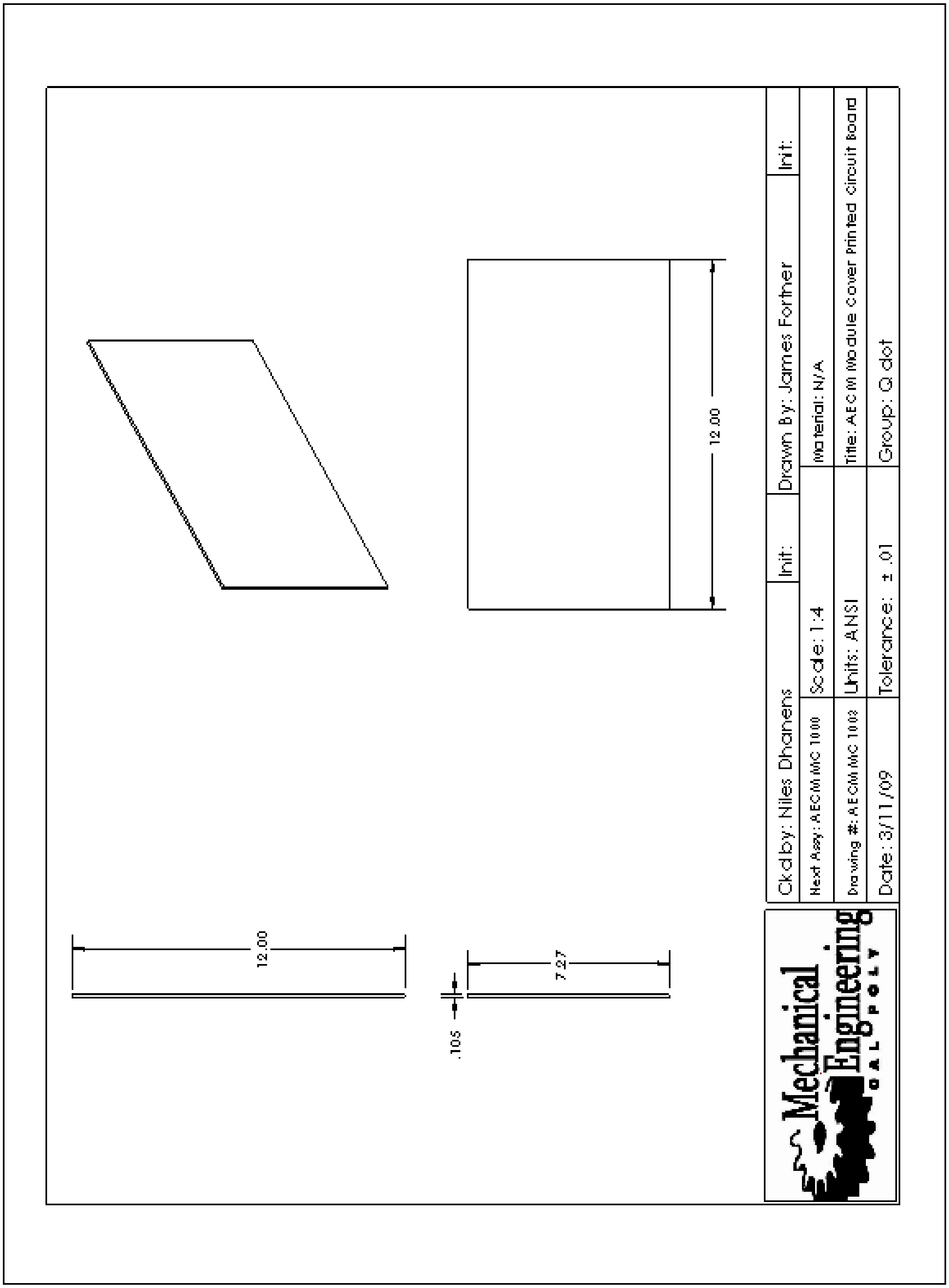
# Appendix C-3 – (AECMMC 1001-Module Cover Left Side)



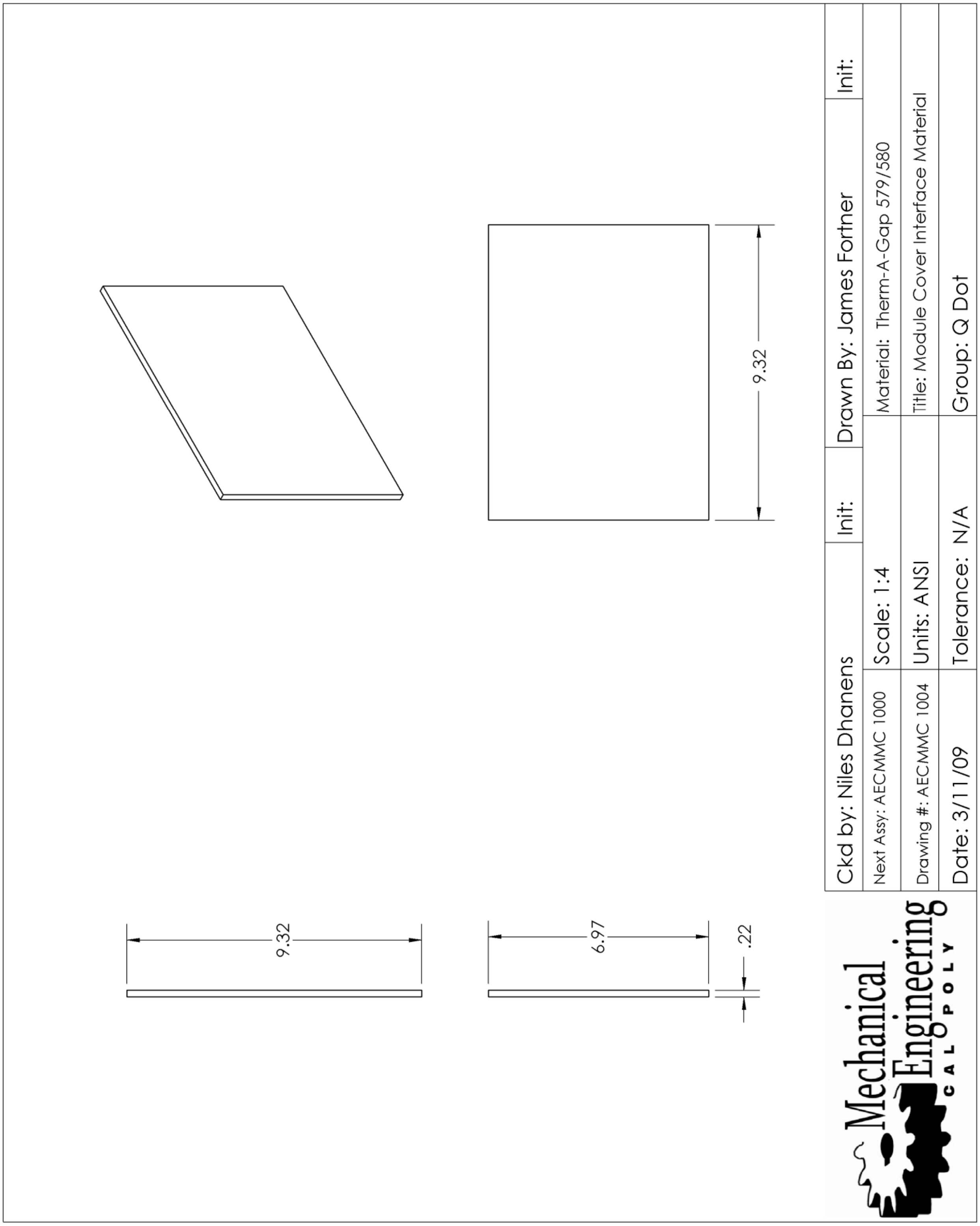
# Appendix C-4 – (AECMMC 1002-Module Cover Right Side)



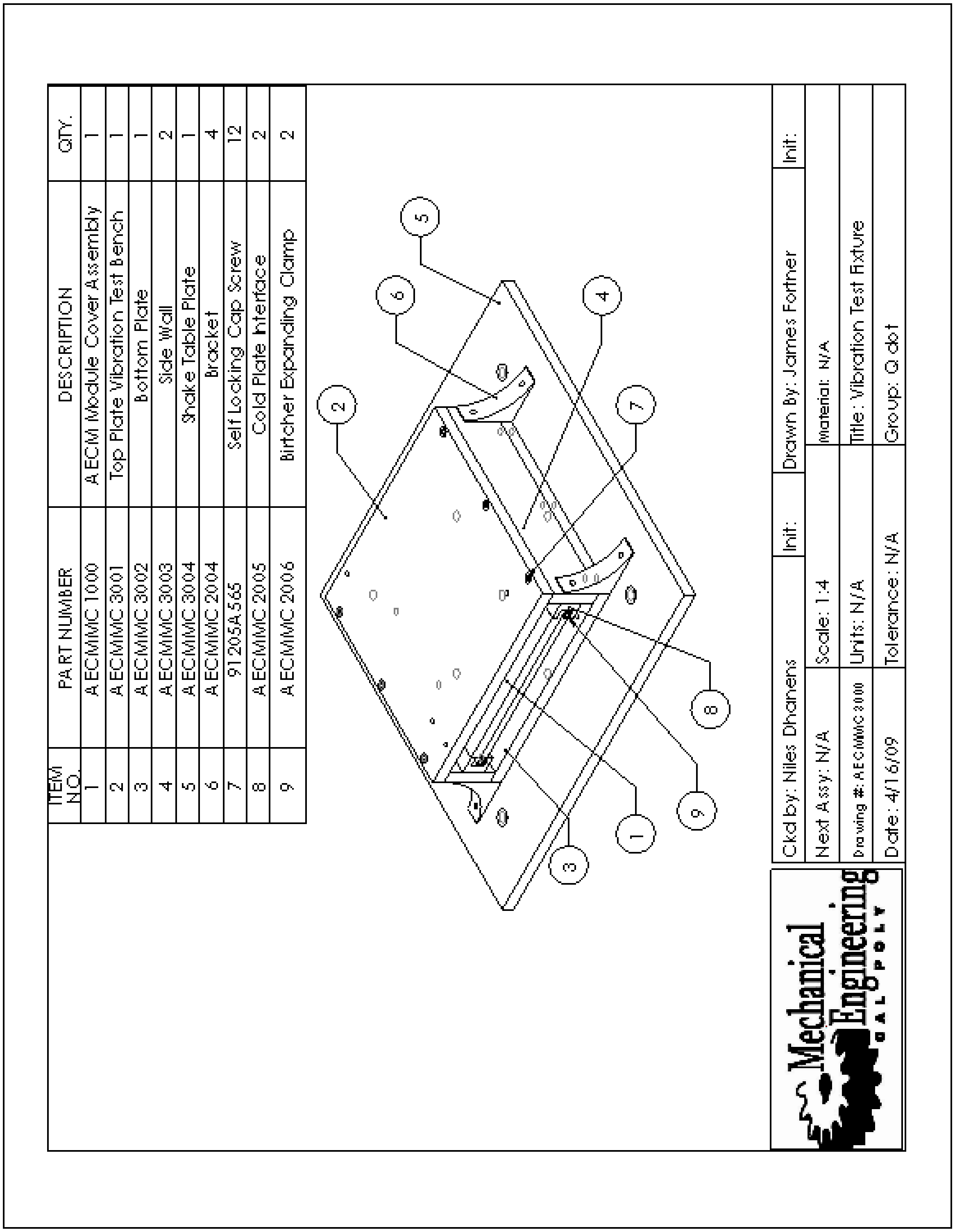
## Appendix C-5 – (AECMMC 1003-Printed Circuit Board)



## Appendix C-6 –(AECMMC 1004-Thermal Interface Material)

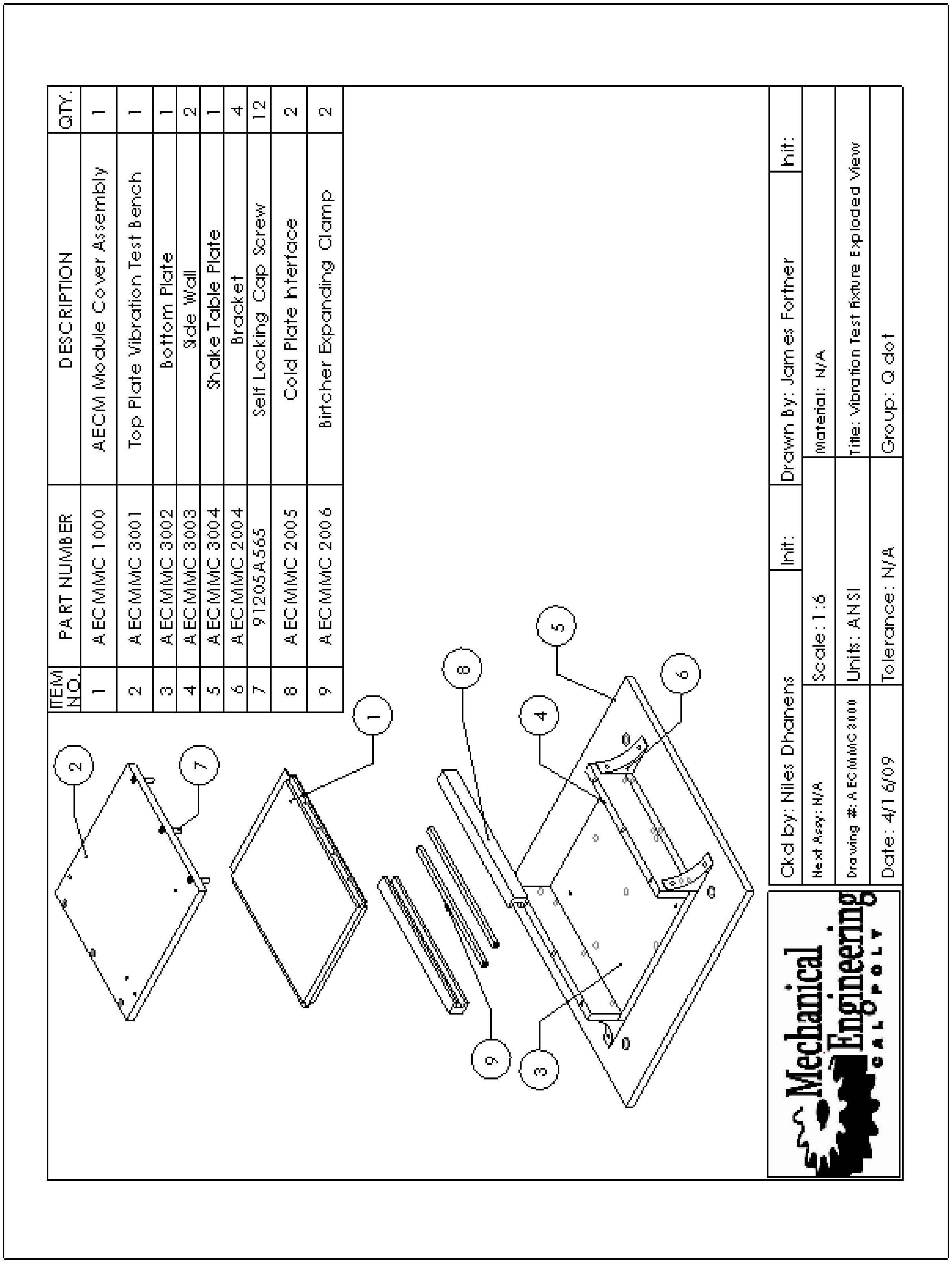


# Appendix C-7 – (AECMMC 3000-Vibration Test Fixture Isometric View)



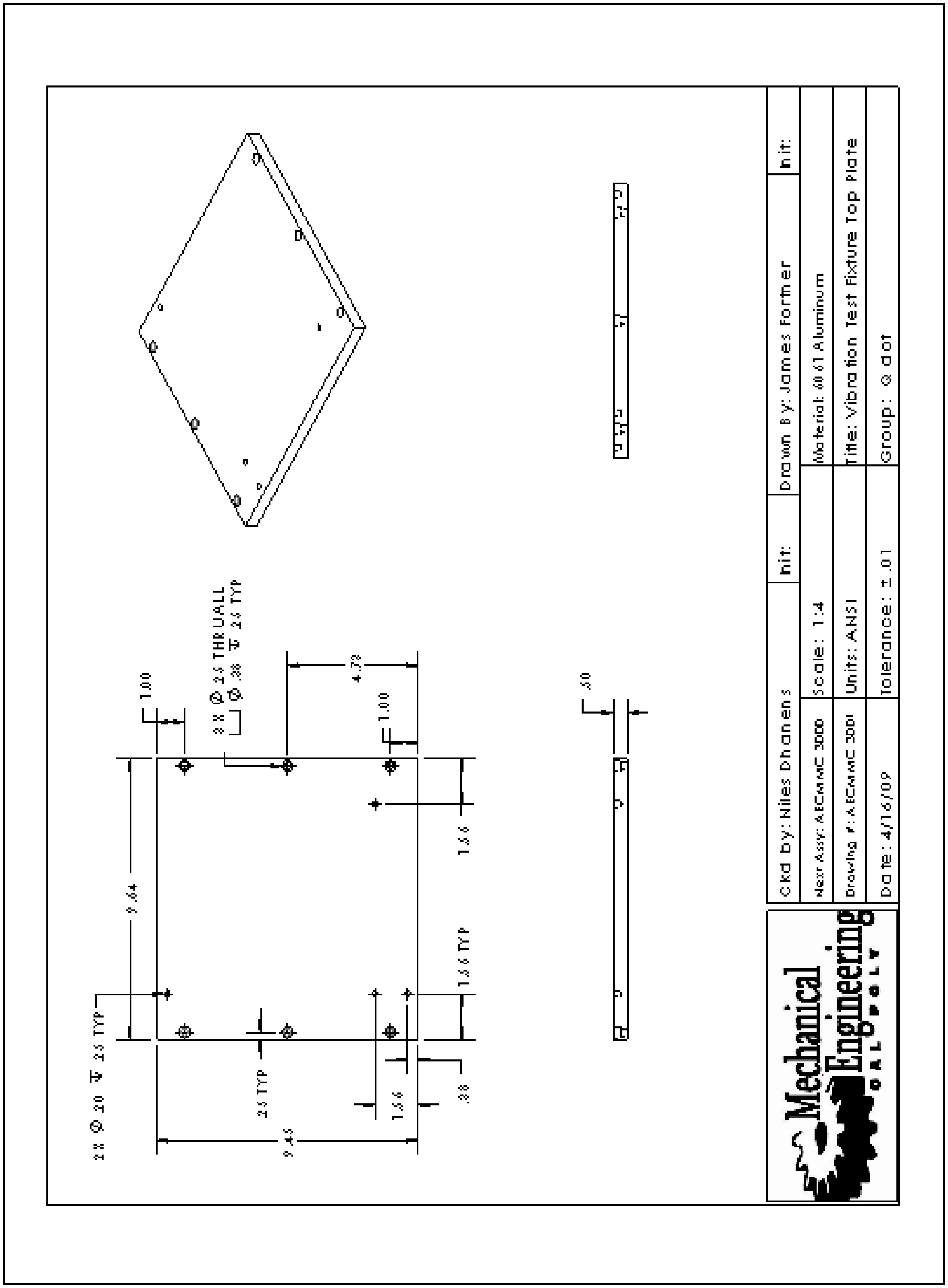

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | AECMMC 1000 | AECM Module Cover Assembly | 1 |
| 2 | AECMMC 3001 | Top Plate Vibration Test Bench | 1 |
| 3 | AECMMC 3002 | Bottom Plate | 1 |
| 4 | AECMMC 3003 | Side Wall | 2 |
| 5 | AECMMC 3004 | Shake Table Plate | 1 |
| 6 | AECMMC 2004 | Bracket | 4 |
| 7 | 91205A565 | Self Locking Cap Screw | 12 |
| 8 | AECMMC 2005 | Cold Plate Interface | 2 |
| 9 | AECMMC 2006 | Birtcher Expanding Clamp | 2 |

# Appendix C-8 – (AECMMC 3000-Vibration Test Fixture Exploded View)

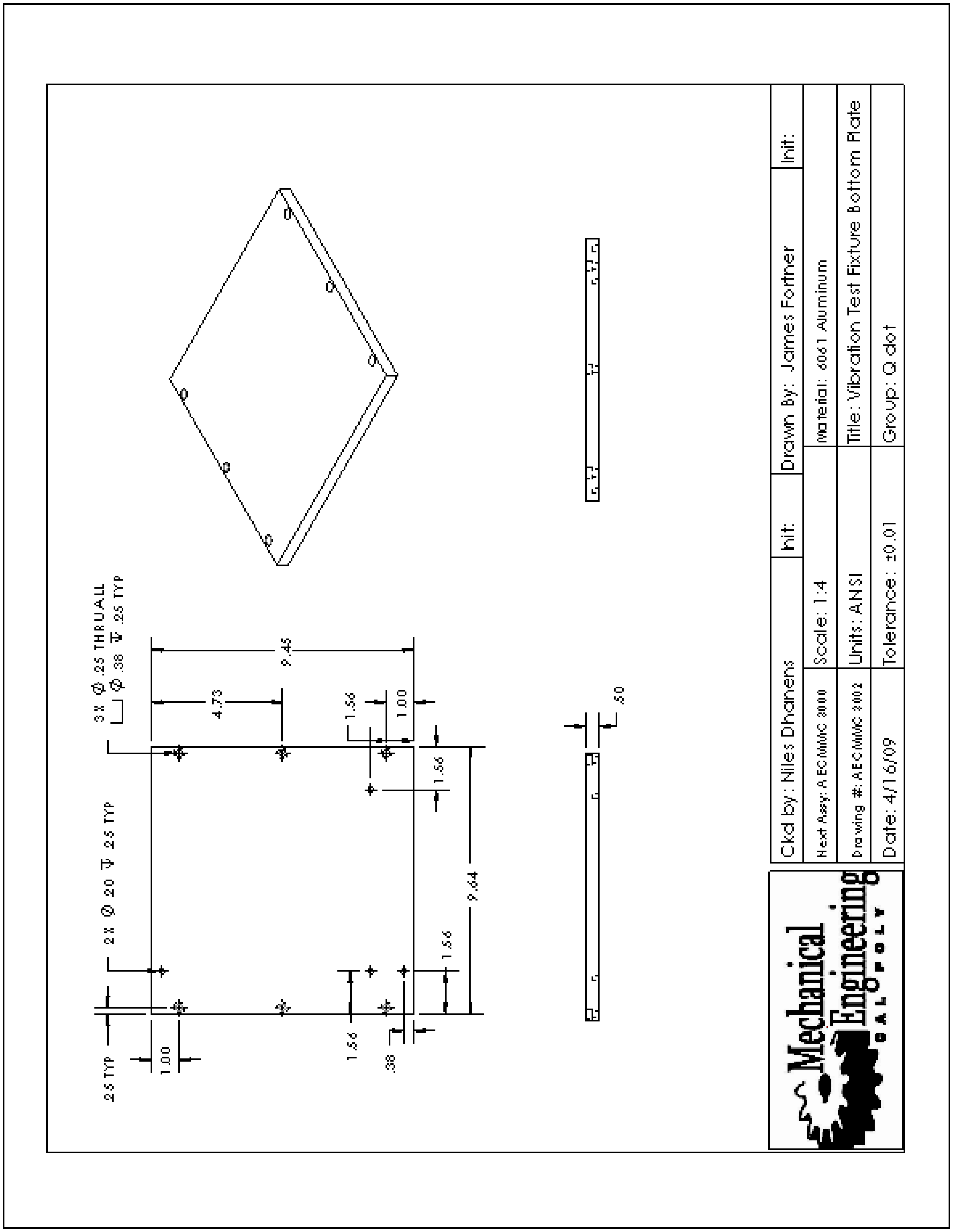



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | AECMMC 1000 | AECM Module Cover Assembly | 1 |
| 2 | AECMMC 3001 | Top Plate Vibration Test Bench | 1 |
| 3 | AECMMC 3002 | Bottom Plate | 1 |
| 4 | AECMMC 3003 | Side Wall | 2 |
| 5 | AECMMC 3004 | Shake Table Plate | 1 |
| 6 | AECMMC 2004 | Bracket | 4 |
| 7 | 91205A565 | Self Locking Cap Screw | 12 |
| 8 | AECMMC 2005 | Cold Plate Interface | 2 |
| 9 | AECMMC 2006 | Birtcher Expanding Clamp | 2 |

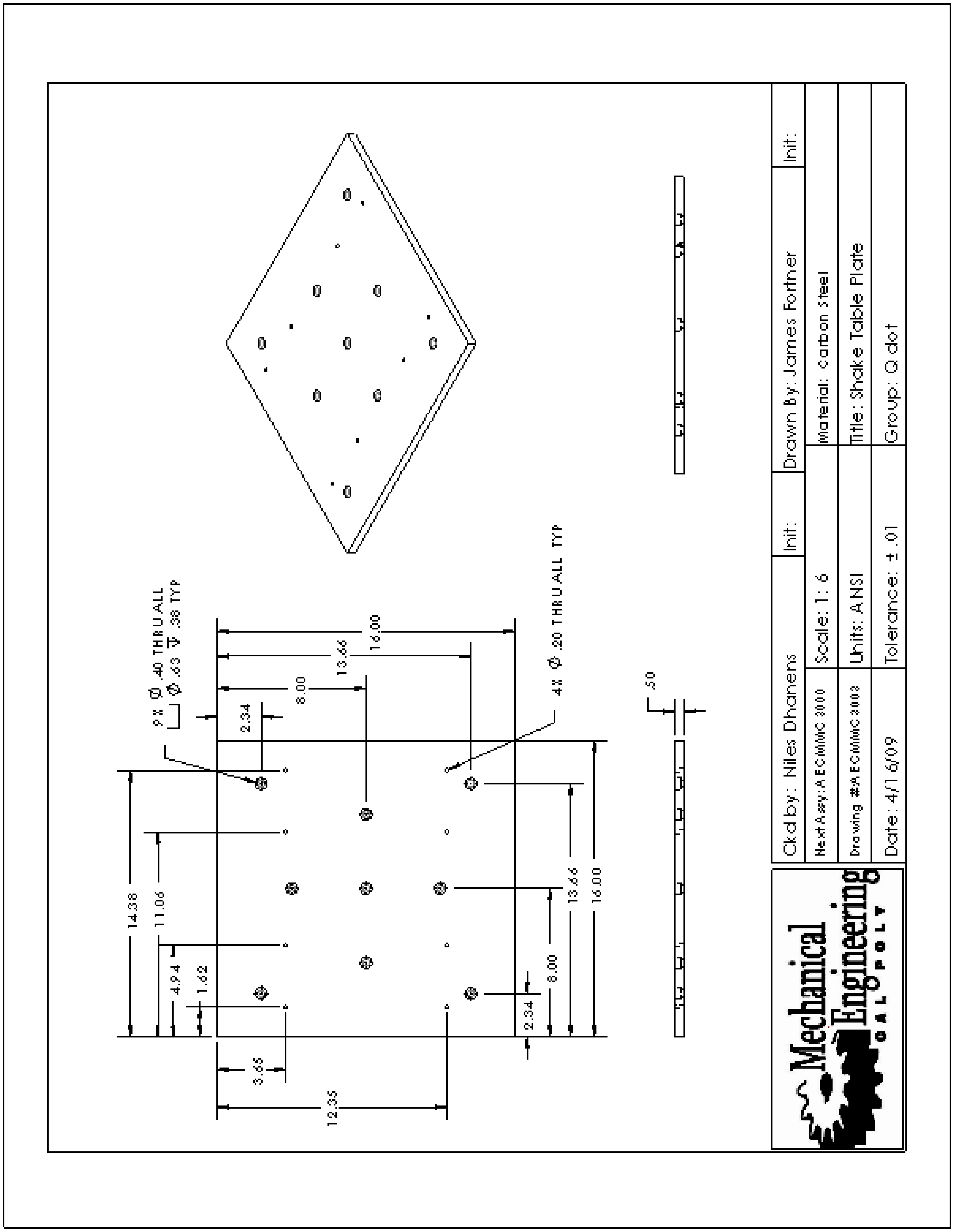
## Appendix C-9 – (AECMMC 3001-Vibration Test Fixture Top Plate)



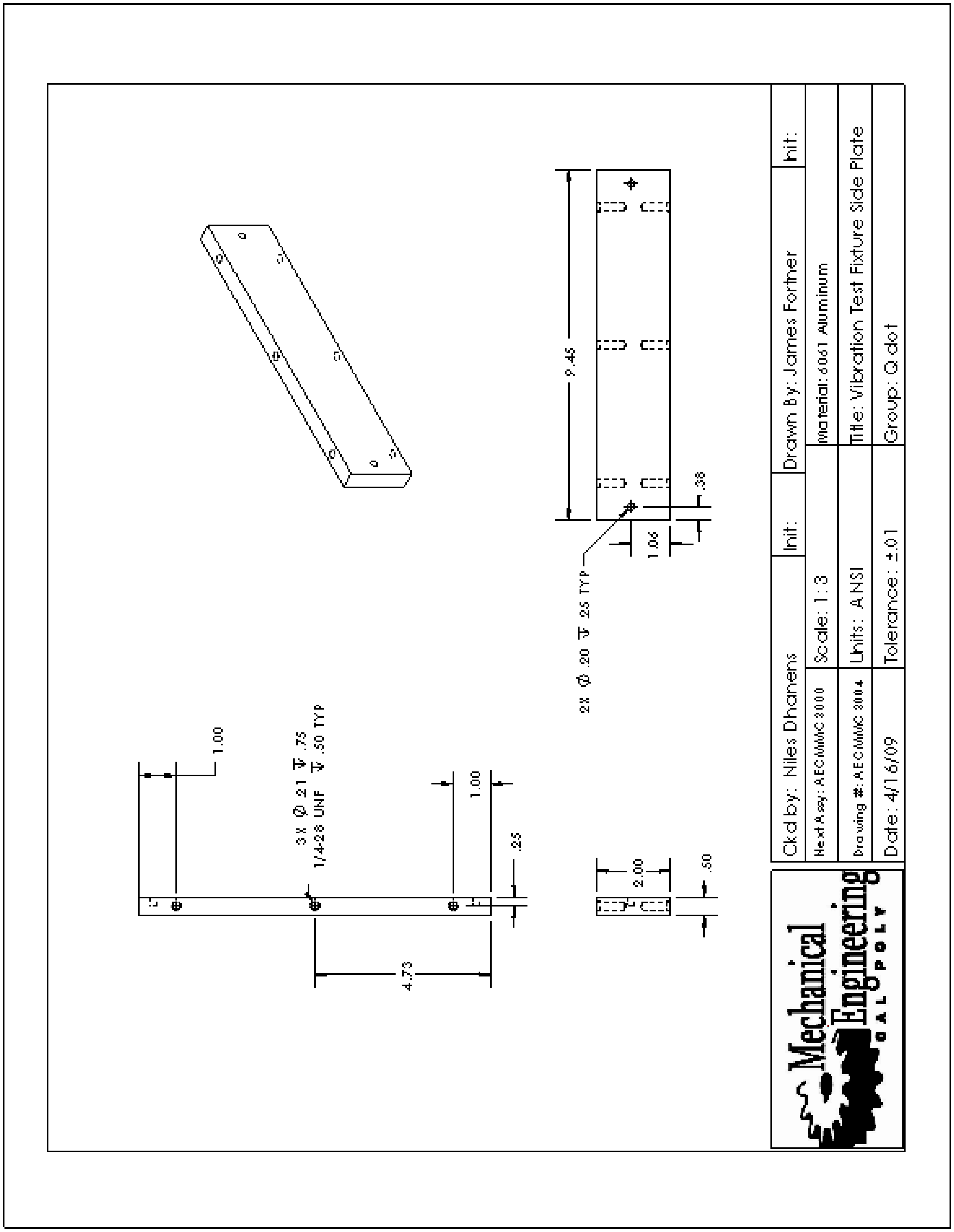
## Appendix C-10 – (AECMMC 3002-Vibration Test Fixture Bottom Plate)



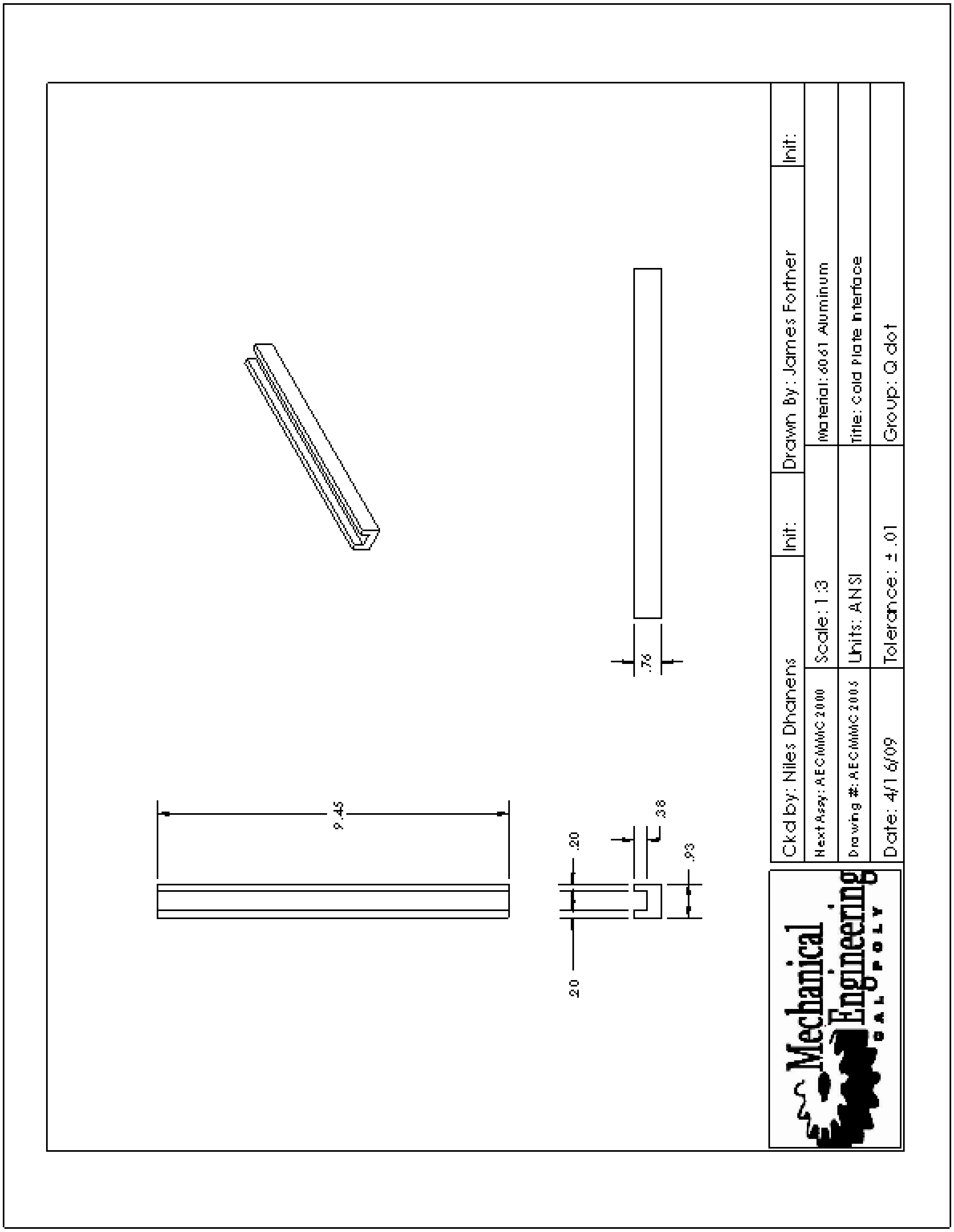
# Appendix C-11 – (AECMMC 3003-Shake Table Plate)



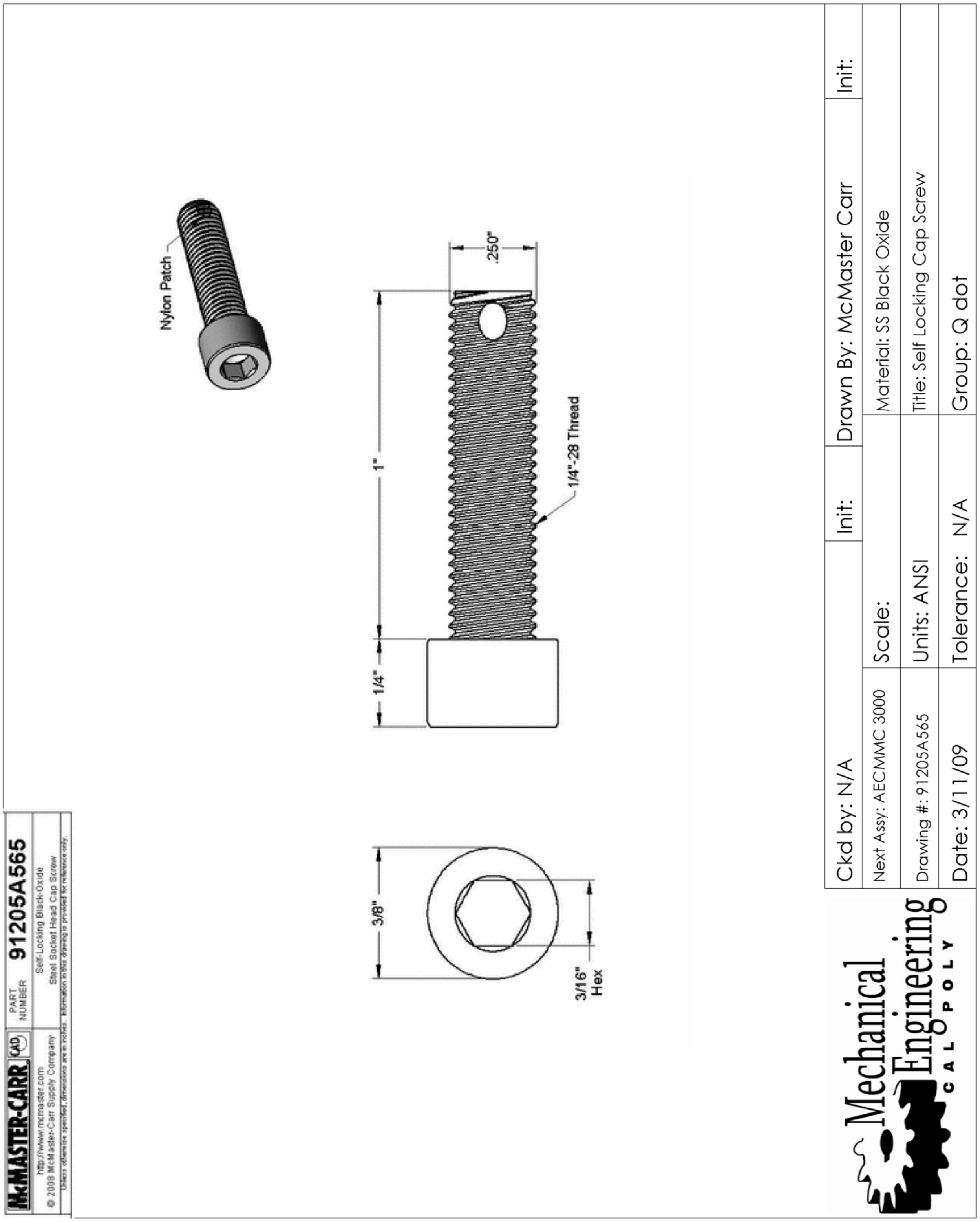
## Appendix C-12 – (AECMMC 3004-Vibration Test Fixture Side Plate)



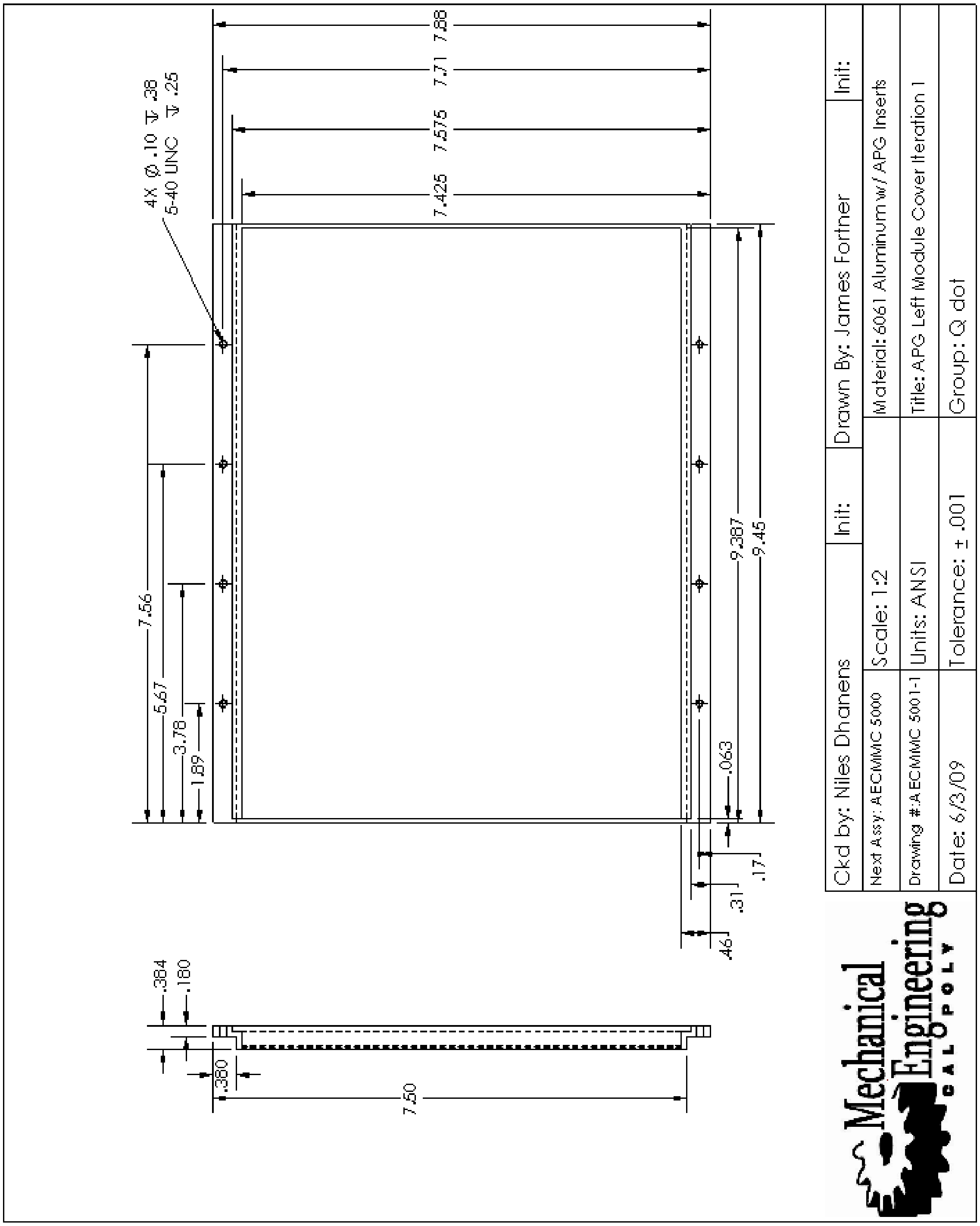
# Appendix C-13 – (AECMMC 3005 Cold Plate Interface)



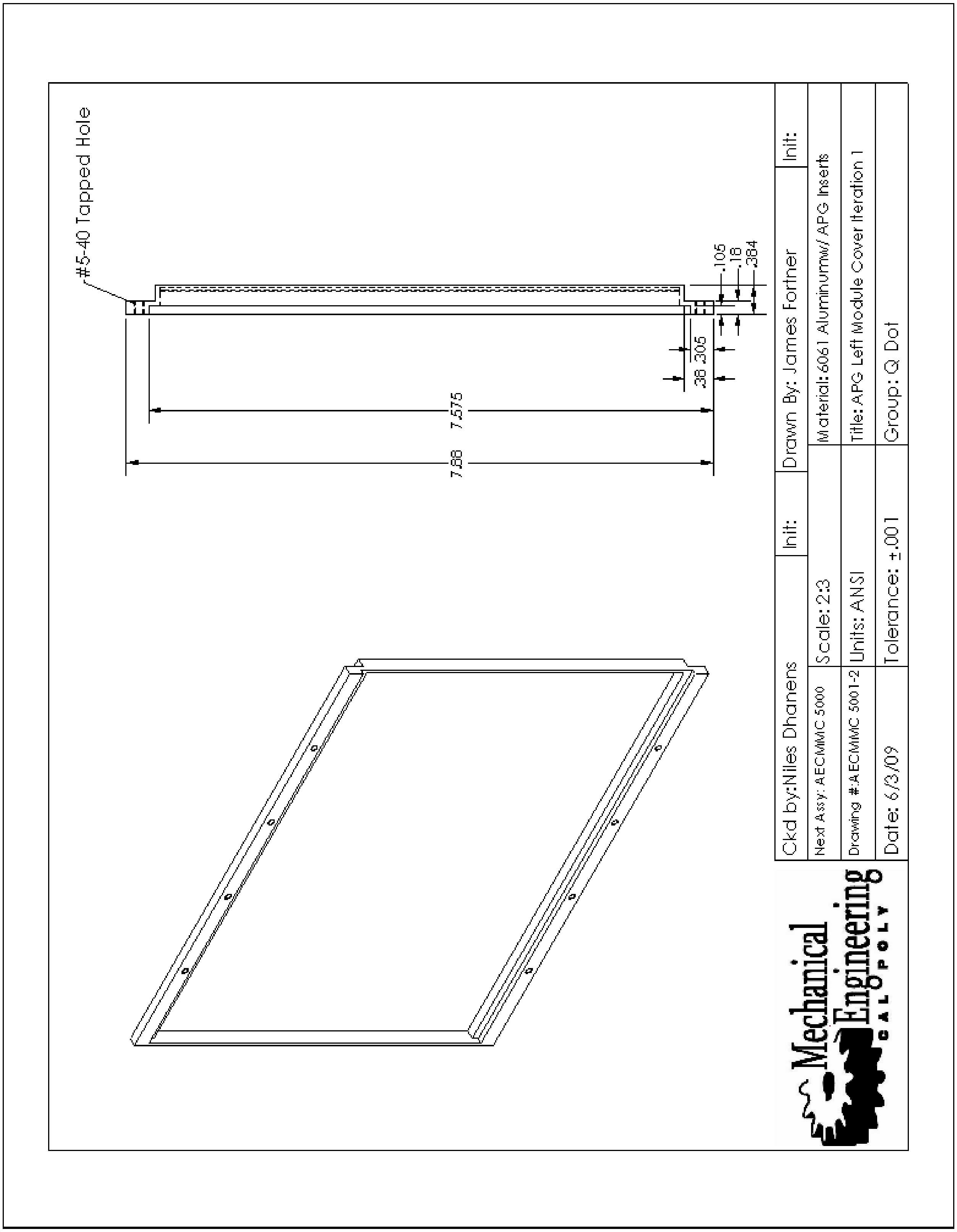
# Appendix C-14 – (91205A565-Self Locking Cap Screw)



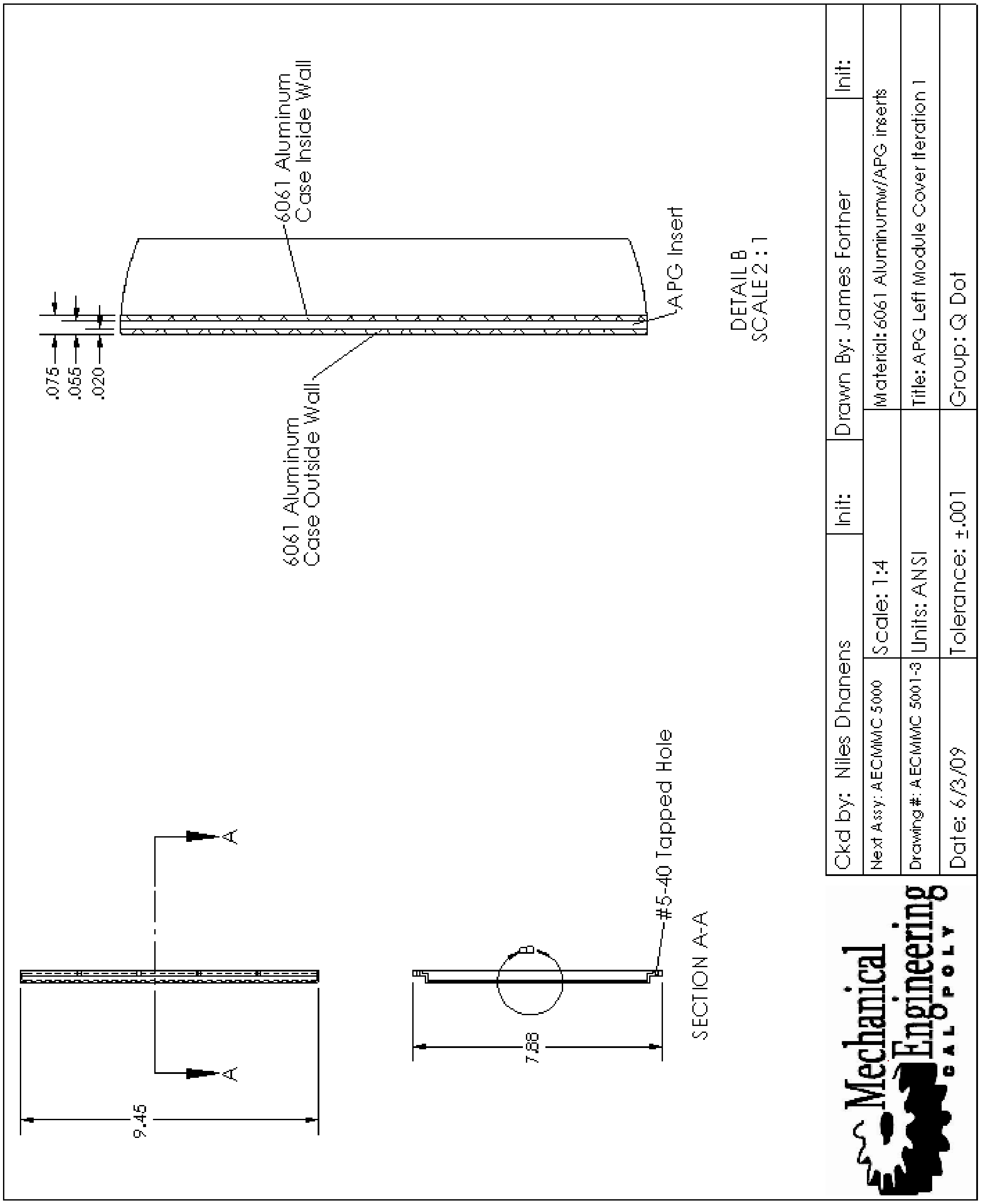
## Appendix C-15 – (AECMMC 5001-1 APG Left Module Cover Iteration 1)



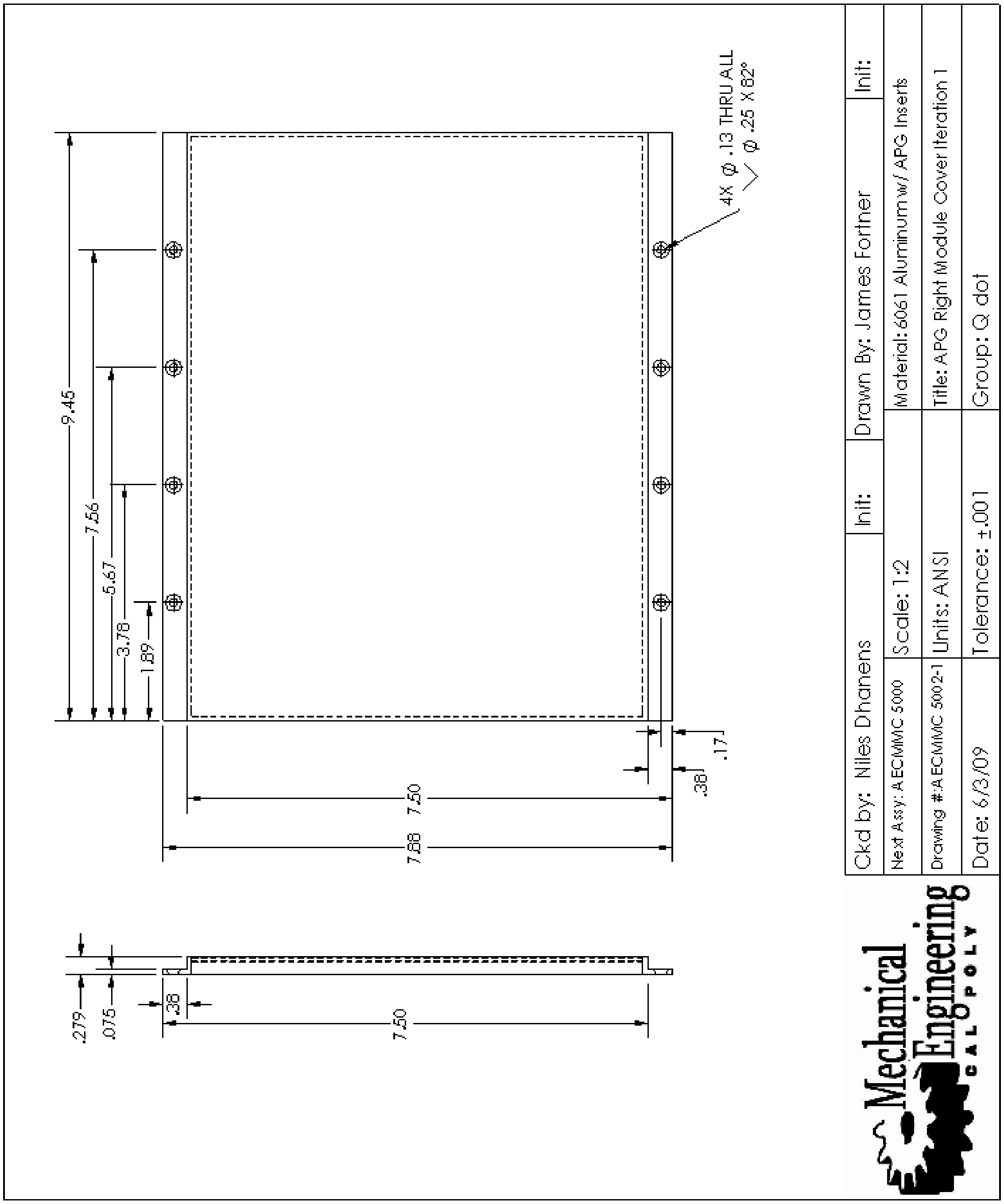
## Appendix C-16 – (AECMMC 5001-2 APG Left Module Cover Iteration 1)



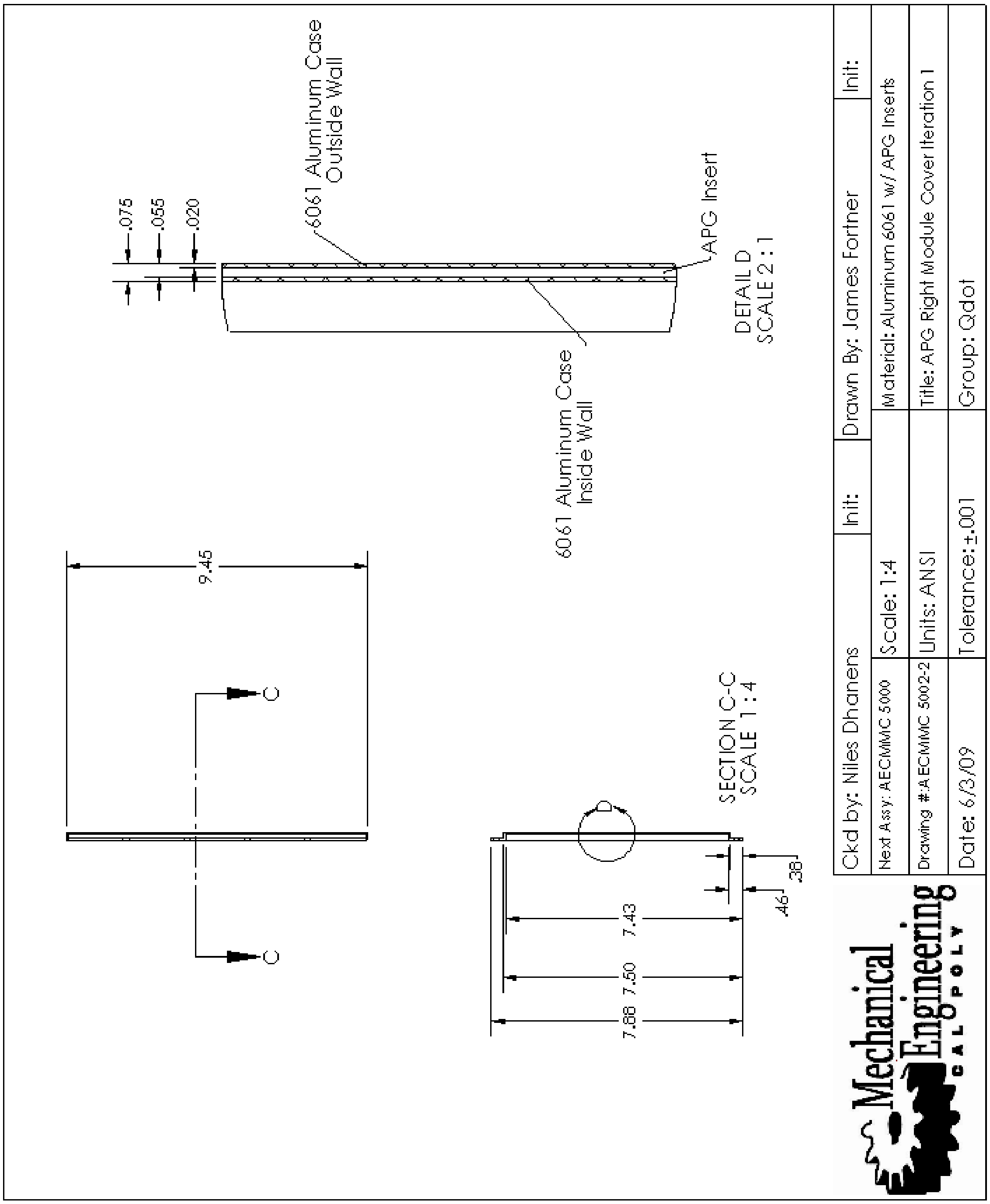
## Appendix C-17 – (AECMMC 5001-3 APG Left Module Cover Iteration 1)



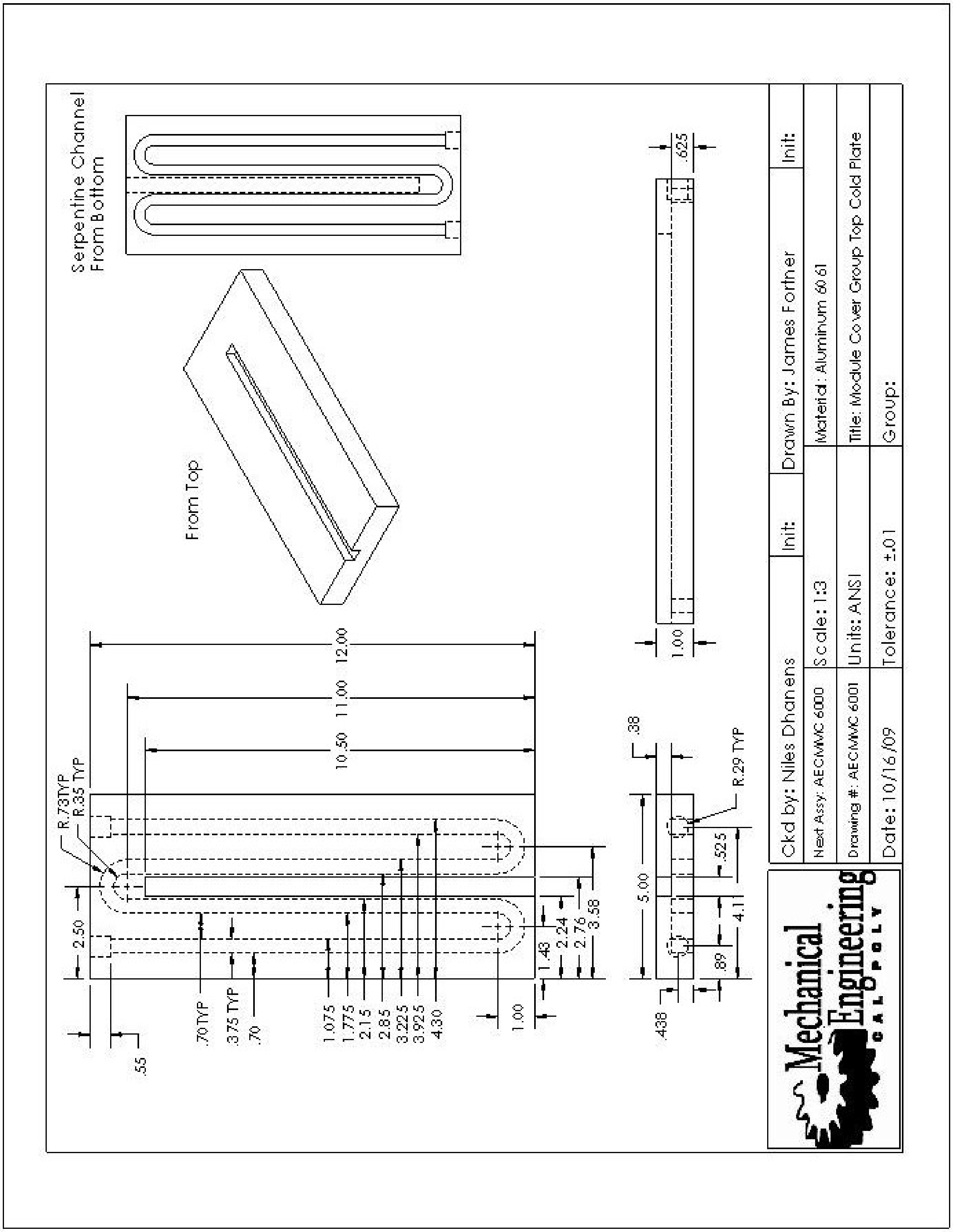
# Appendix C-18 – (AECMMC 5002-1 APG Right Module Cover Iteration 1)



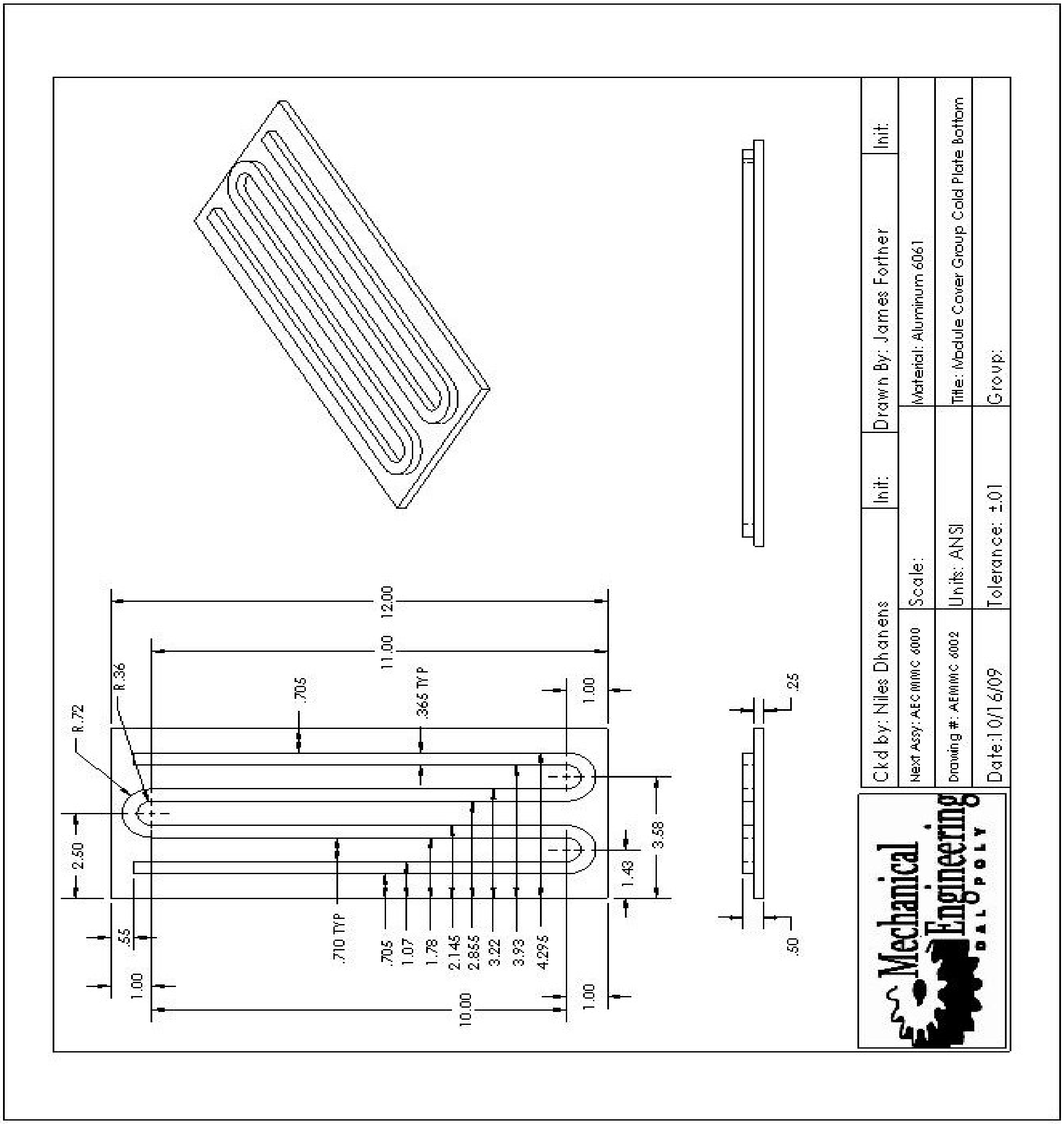
## Appendix C-19 – (AECMMC 5002-2 APG Right Module Cover Iteration 1)



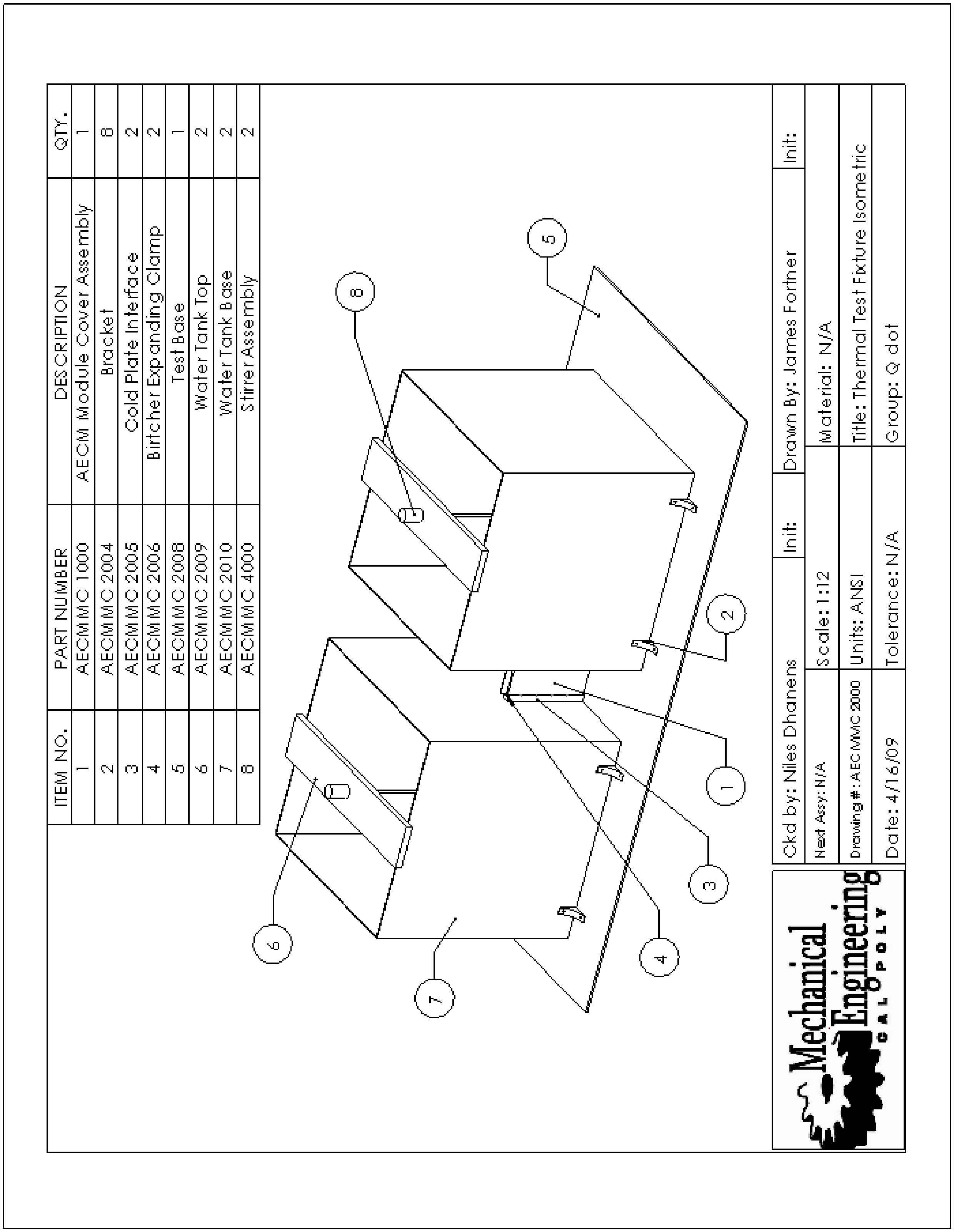
## Appendix C-20 – (AECMMC 6001 Cold Plate Bottom)



# Appendix C-21 – (AECMMC 6002 Cold Plate Bottom)

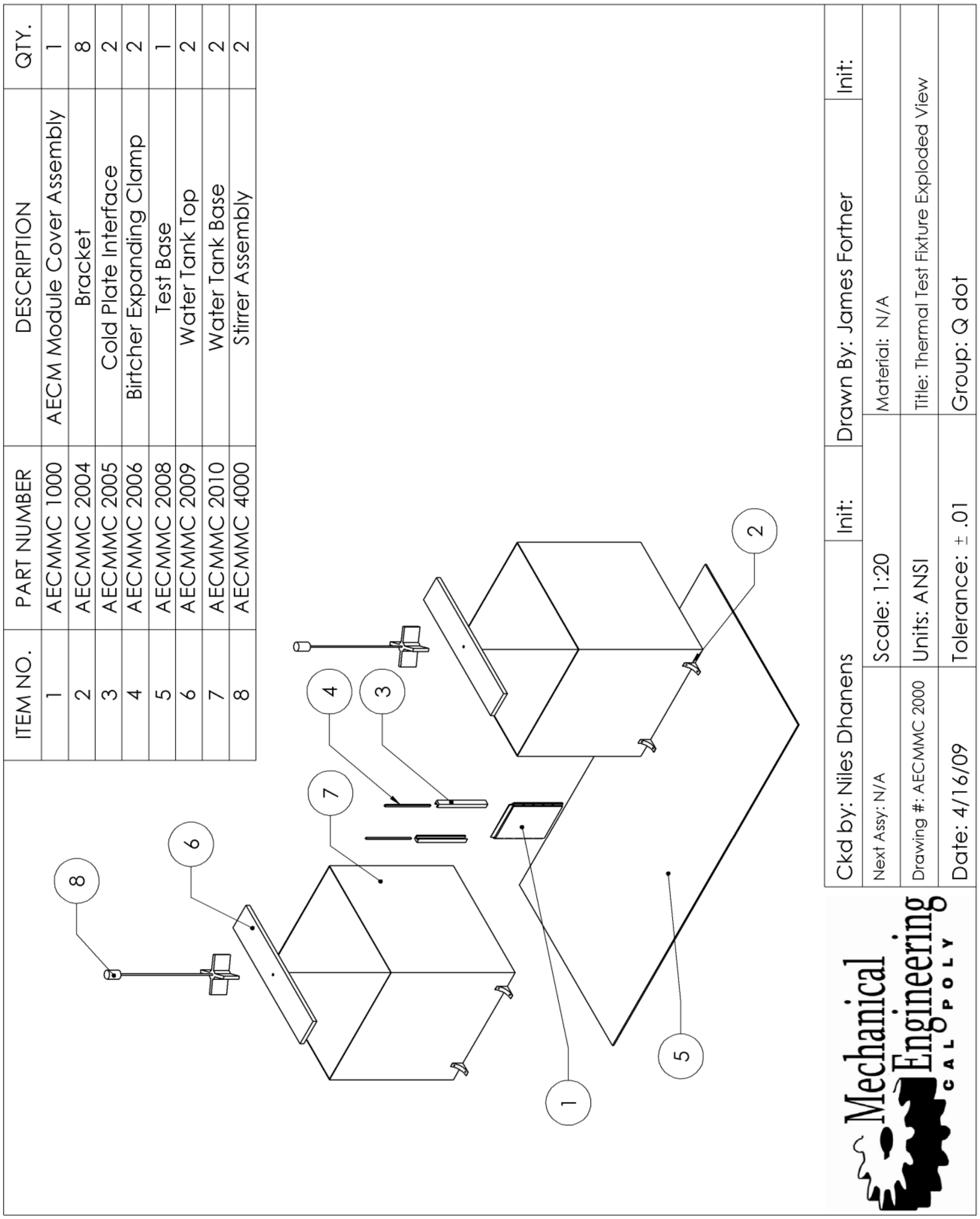


## Appendix C-22 – (AECMMC 2000-Thermal Test Fixture Isometric View)



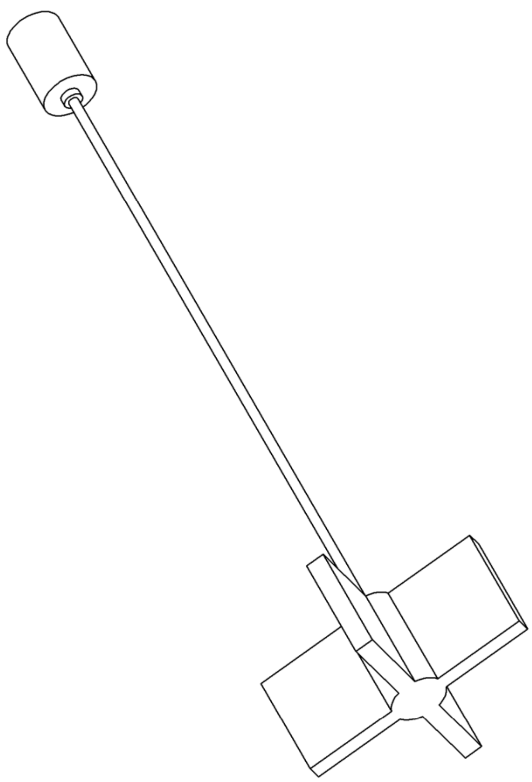

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | AECMMC 1000 | AECM Module Cover Assembly | 1 |
| 2 | AECMMC 2004 | Bracket | 8 |
| 3 | AECMMC 2005 | Cold Plate Interface | 2 |
| 4 | AECMMC 2006 | Birtcher Expanding Clamp | 2 |
| 5 | AECMMC 2008 | Test Base | 1 |
| 6 | AECMMC 2009 | Water Tank Top | 2 |
| 7 | AECMMC 2010 | Water Tank Base | 2 |
| 8 | AECMMC 4000 | Stirrer Assembly | 2 |

# Appendix C-23 – (AECMMC 2000-Thermal Test Fixture Exploded View)



## Appendix C-24 – (AECMMC 40000-Stir Assembly Isometric View)

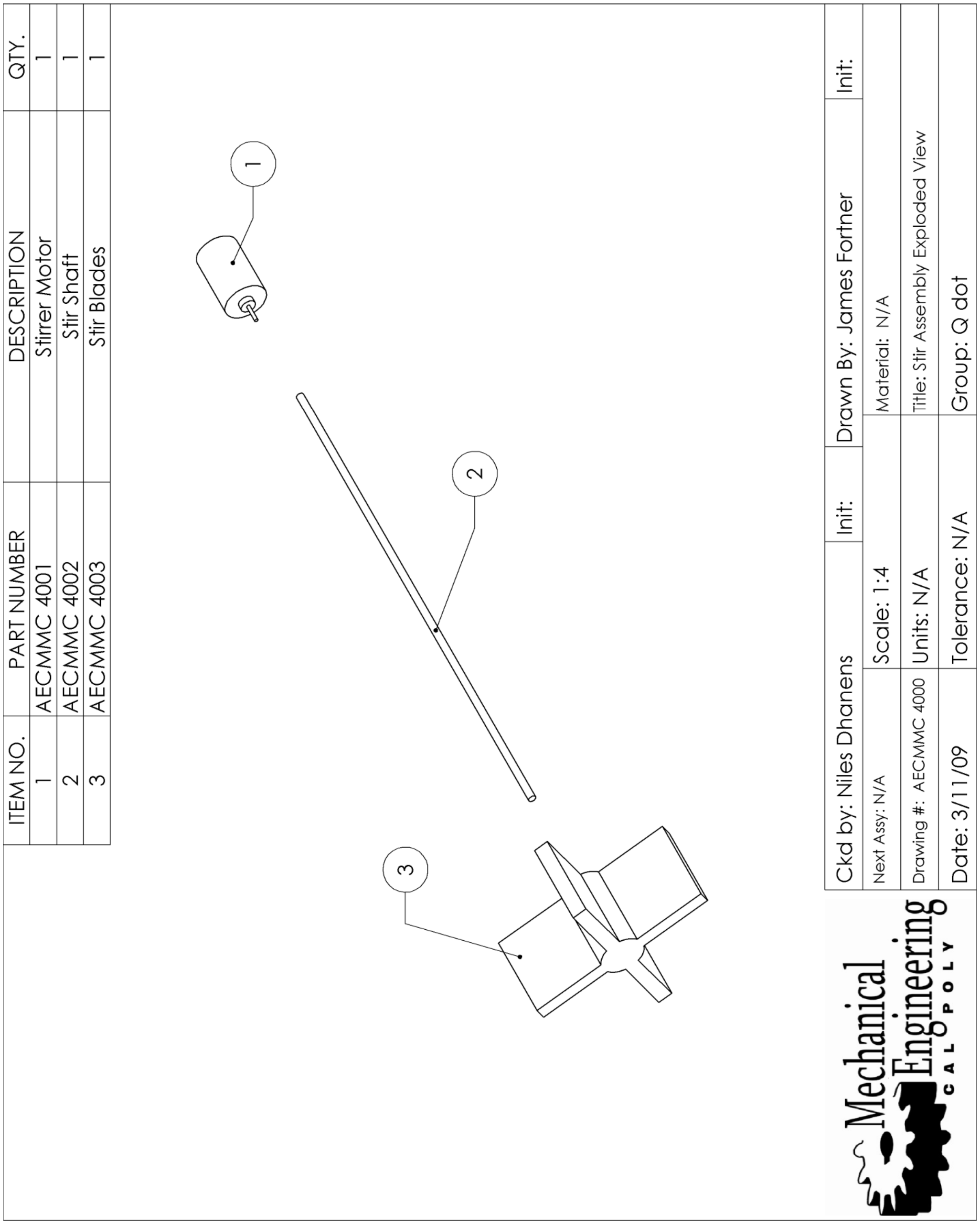
| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | AECMMC 4001 | Stirrer Motor | 1 |
| 2 | AECMMC 4002 | Stir Shaft | 1 |
| 3 | AECMMC 4003 | Stir Blades | 1 |



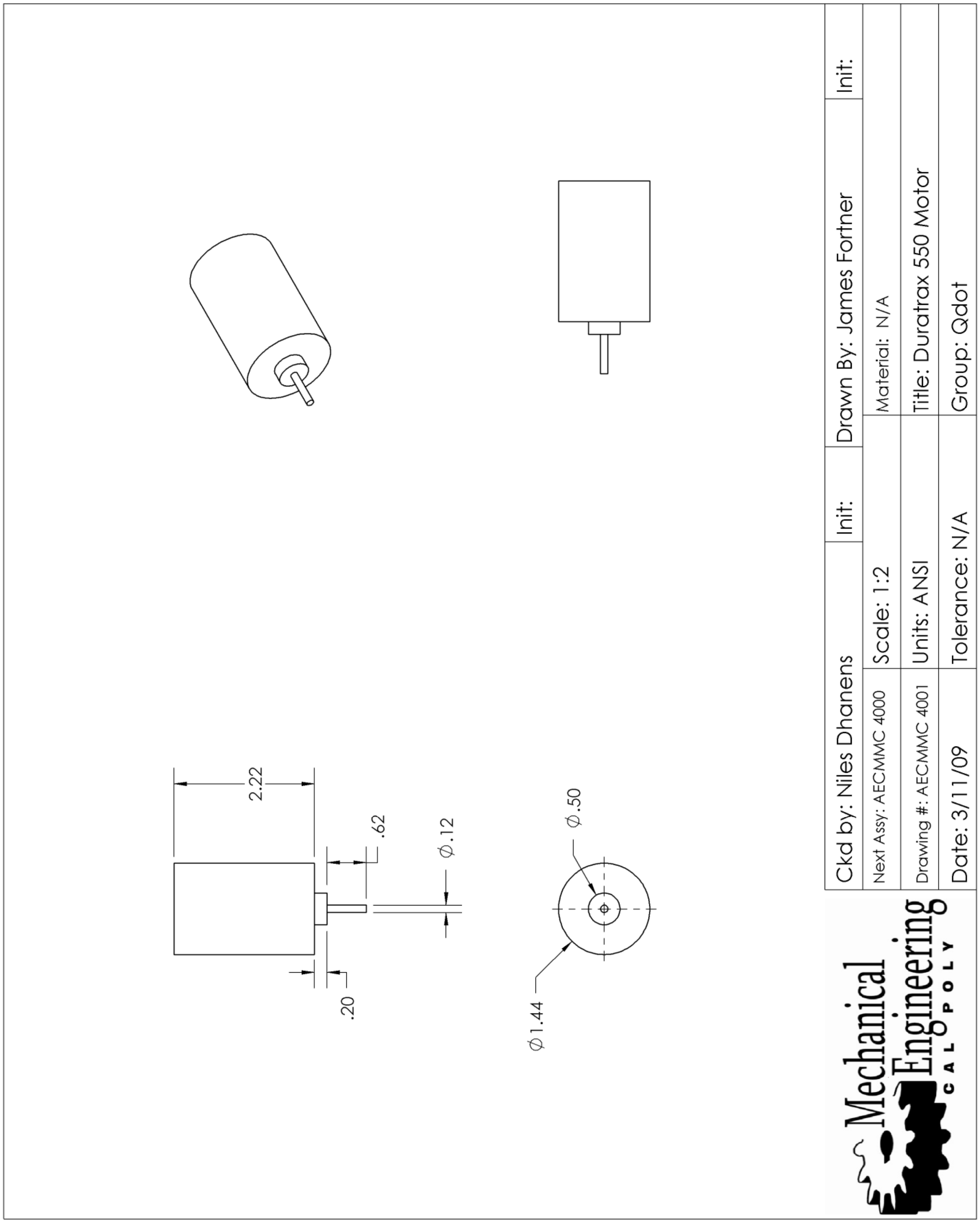
| | | | |
|---|---|---|---|
| Ckd by: Niles Dhanens | Init: | Drawn By: James Fortner | Init: |
| Next Assy: N/A | Scale: 1:4 | Material: N/A | |
| Drawing #:AECMMC 4000 | Units: N/A | Title: Stir Assembly Isometric | |
| Date: 3/11/09 | Tolerance: N/A | Group: Q dot | |

Mechanical Engineering CAL POLY

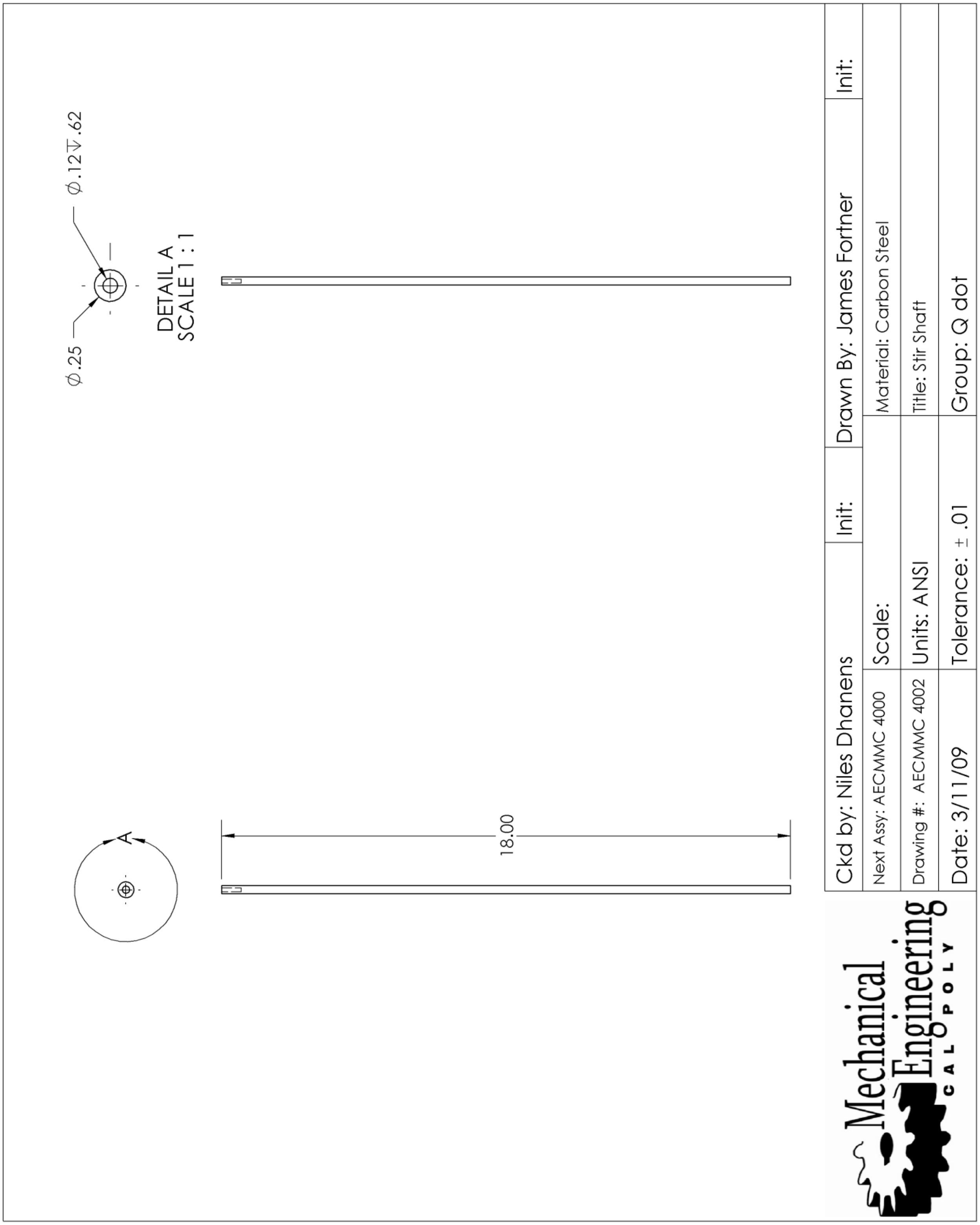
# Appendix C-25 – (AECMMC 4000-Stir Assembly Exploded View)



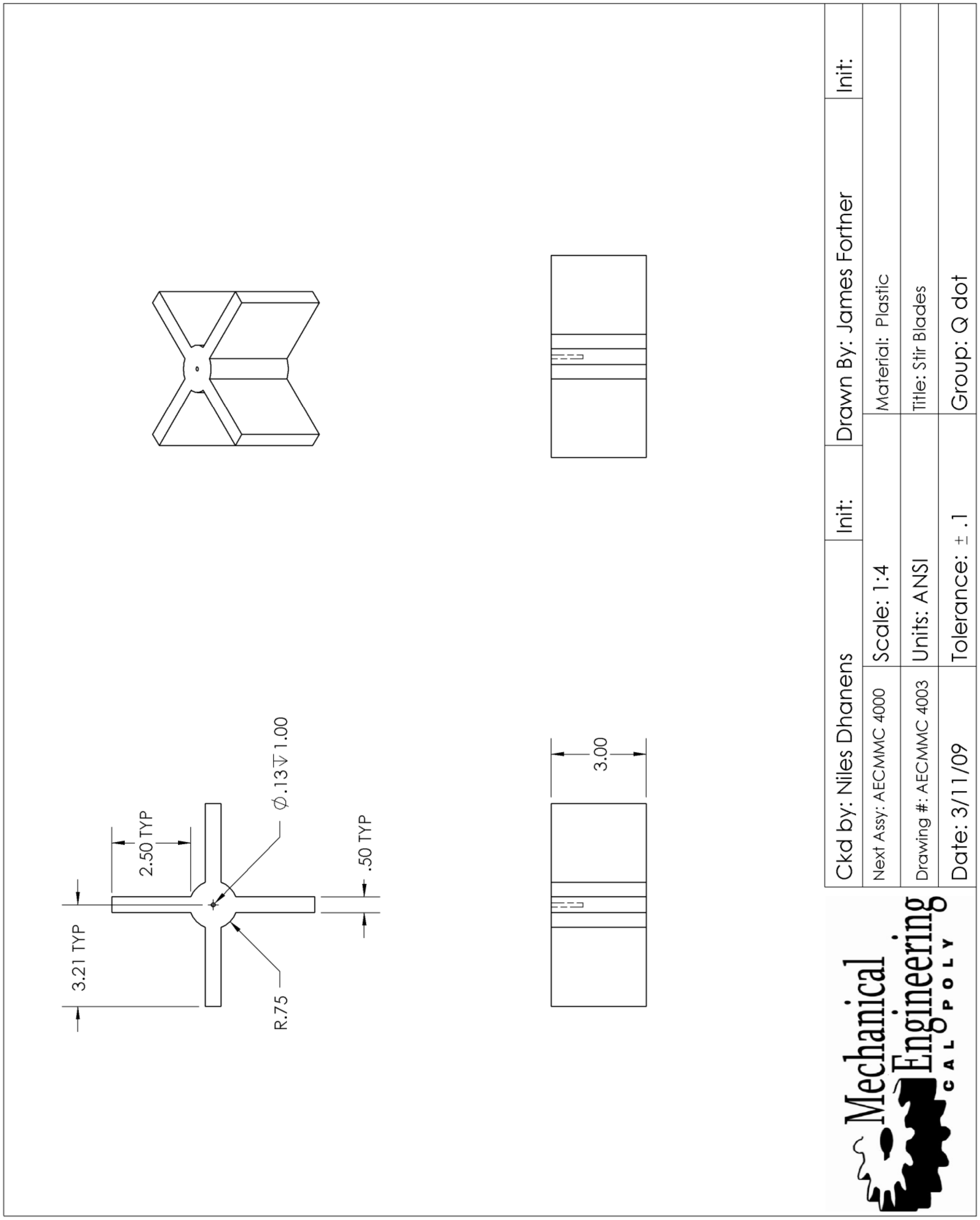
# Appendix C-26 – (AECMMC 4001-Duratrax 550 Motor)



# Appendix C-27 – (AECMMC 4002-Stir Shaft)



# Appendix C-28 – (AECMMC 4003-Stir Blades)



# Appendix D-1 – Timeline Spring Quarter

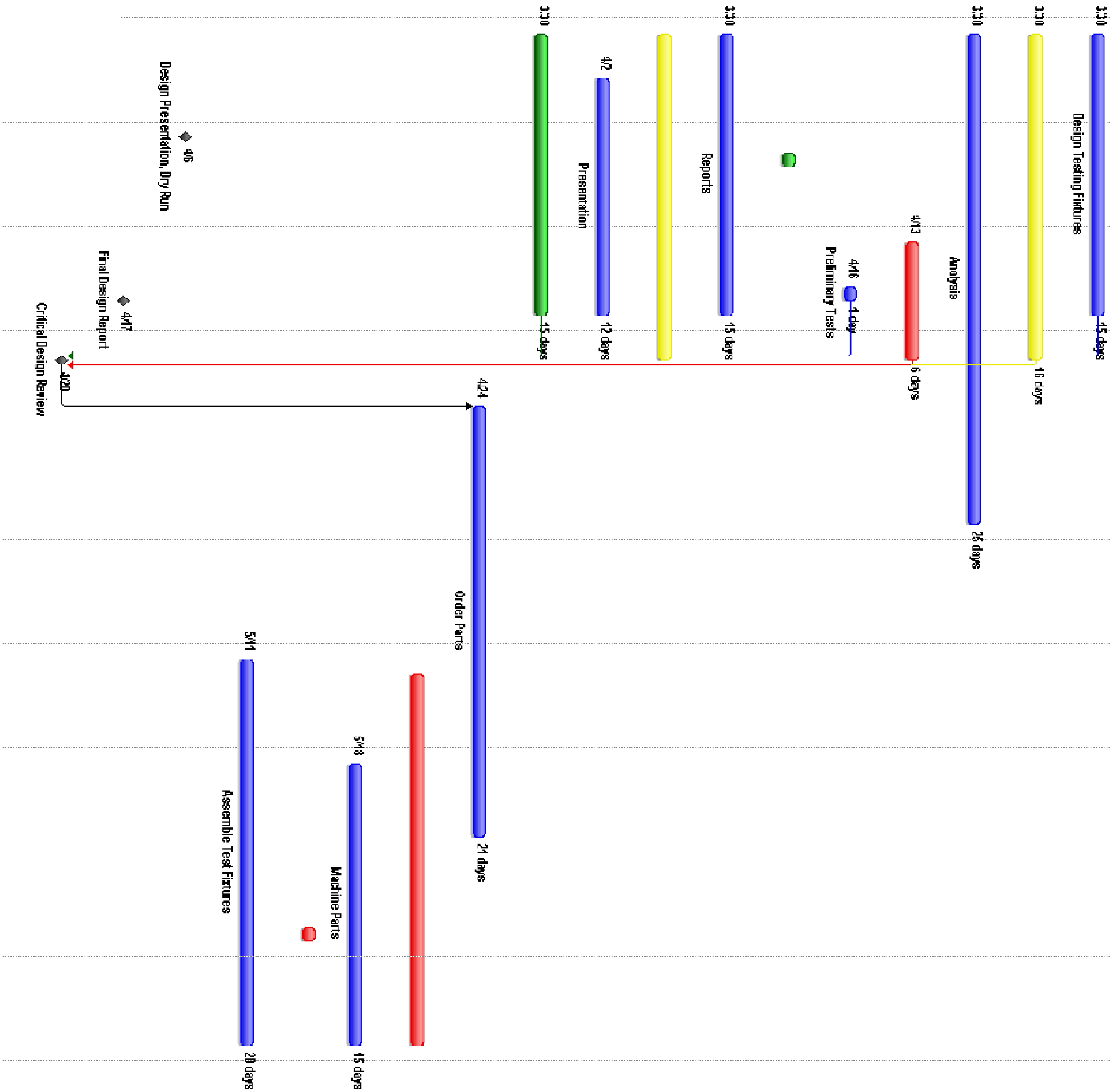



**Figure D-1.** Spring quarter Gantt chart Showing initial proposed task time (blue) verses actual task time beneath (red = behind, yellow = late but no affect on timeline, green = on time.

# Appendix D-2 – Timeline Fall Quarter

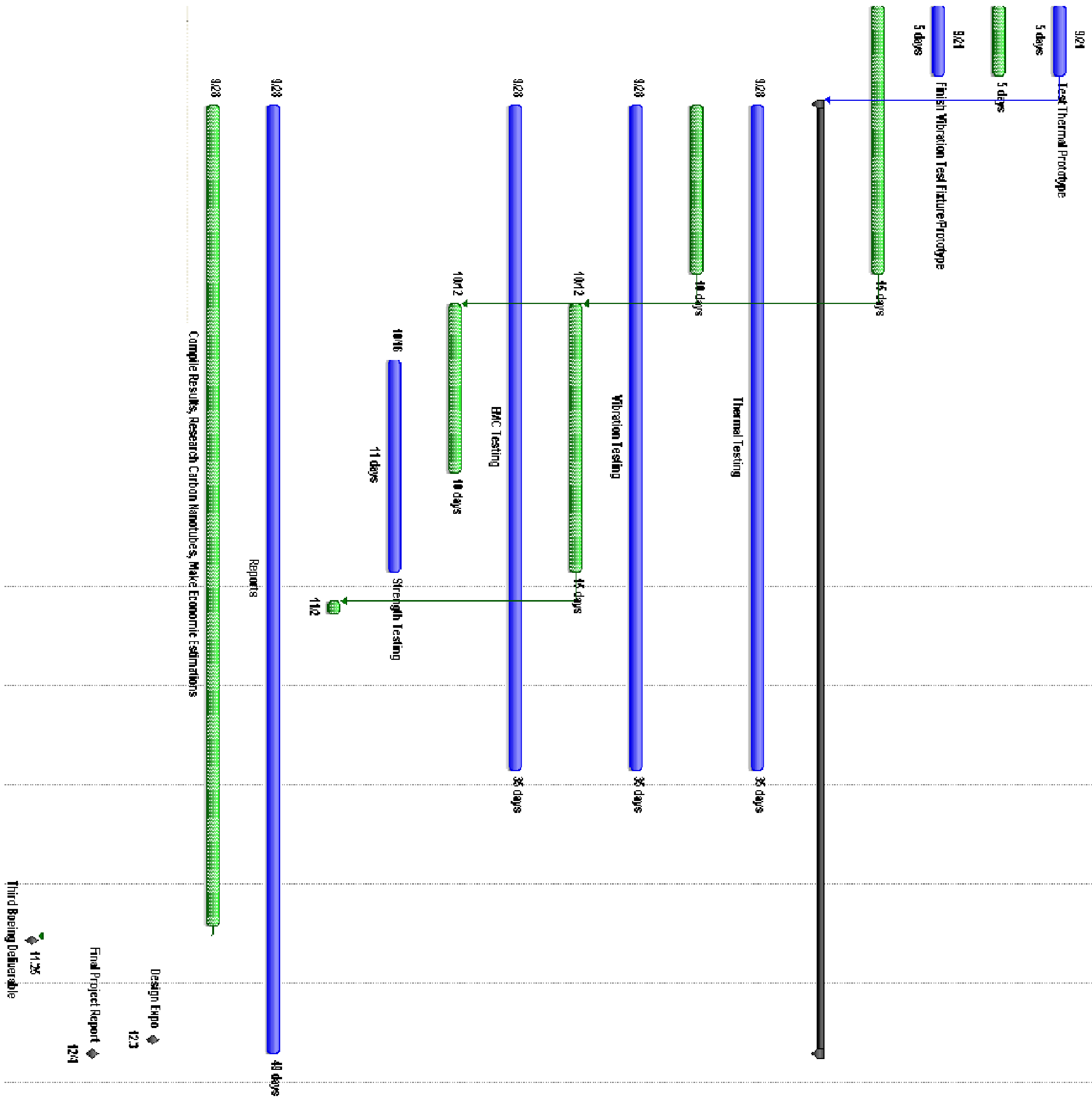



**Figure D-2.** Fall quarter Gantt chart Showing initial proposed task time (blue) verses modified proposed task time beneath (green).

## Appendix E - Wort Chiller Information and Analysis

**Background**
Wort Chillers are commonly used by home beer brewers in order to cool their wort down from boiling so that the brewer can add more yeast and lower the chance of bacterial spoilage. Although this is a common use for this device, similar devices are used in a number of heat transfer applications.

The wort chiller is essentially a helical heat exchanger. The chiller is manufactured using copper tubing of varying diameters and wall thicknesses depending upon operating conditions. The simplest and most widely used chiller design is known as an immersion chiller. An immersion chiller (seen below, Fig E-1) is made by bending copper tubing into a spiral shape. The coils of copper align vertically but have space between them to allow for water movement between coils. There is one inlet and one outlet used to circulate water. Water is forced into the inlet of the chiller and the pressure circulates the water through the chiller. Once the water reaches the outlet, typically the water is sent to a drain and not reused. Our thermal test fixture will utilize a immersion chiller in order to carry away heat from the water reservoirs as each module cover design is tested.

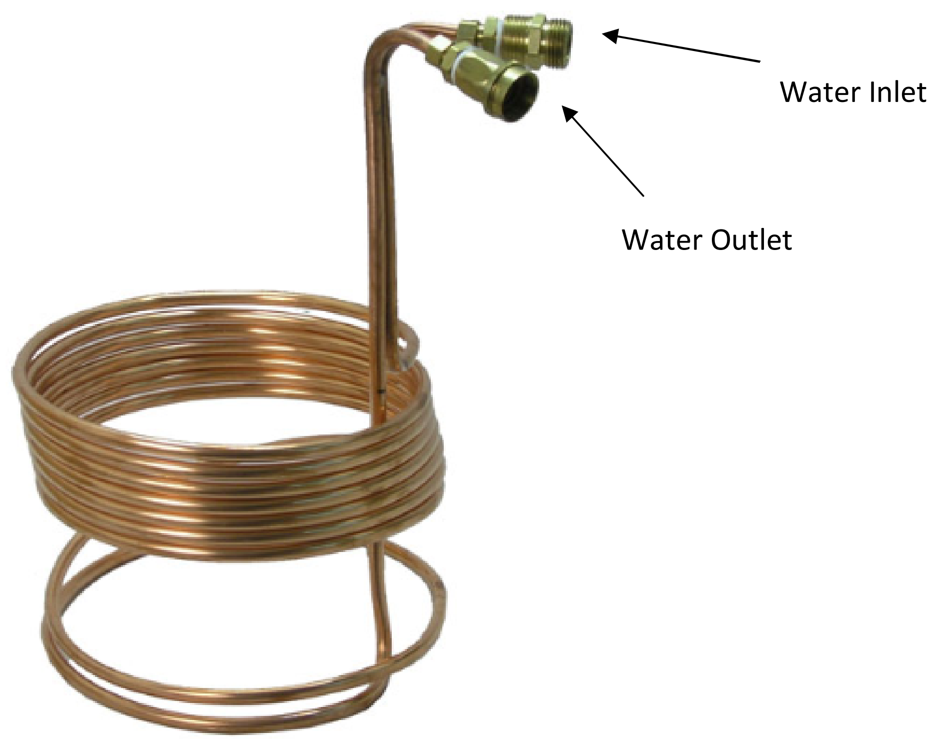



**Figure E-1**. Typical Immersion Wort Chiller with Inlet and Outlet for cooling fluid circulation.

**Theory**
Helical heat exchangers are used because of the high rate of convective heat transfer. Because of the helical shape, there is an "induced secondary flow" (Incropera). Due to the fact that the liquid is circulating around a diameter and not flowing through a straight pipe, vortices are formed along the wall of the pipe. These vortices cause increased mixing of the fluid and disrupt the boundary layer on the pipe surface. The increase in mixing causes non-uniform local heat transfer coefficients around the periphery of the pipe. Analysis of helical heat exchangers is difficult and average convection coefficients are needed in order to gain an estimate of heat transfer. However, although the analysis is difficult, it has been shown that the helical shape increases the amount of convective heat transfer in contrast to that of a straight pipe.

**Experimental Data**
A wort chiller designed for use in a 5 gallon tank was purchased from Doc' Cellar, a local home brewing shop in San Luis Obispo, CA. A steel cooking pot was filled with 3 gallons of water and was brought to a boil. After brought to a boil, the tank was covered with a lid and insulated using cloth. A thermometer was placed in the tank fluid as well as in a reservoir into which the chiller outlet fluid drained into. This reservoir was used to measure the outlet fluid temperature. Once the tank was insulated, water was circulated through the system and measurements were taken every 2 minutes. Effort was made to try to reduce the amount of natural convection while taking measurements, however, some did occur. Convection from the tank was neglected for the purpose of this experiment. The thermodynamic analysis of the system as a whole are seen below in the analysis section of Appendix E.

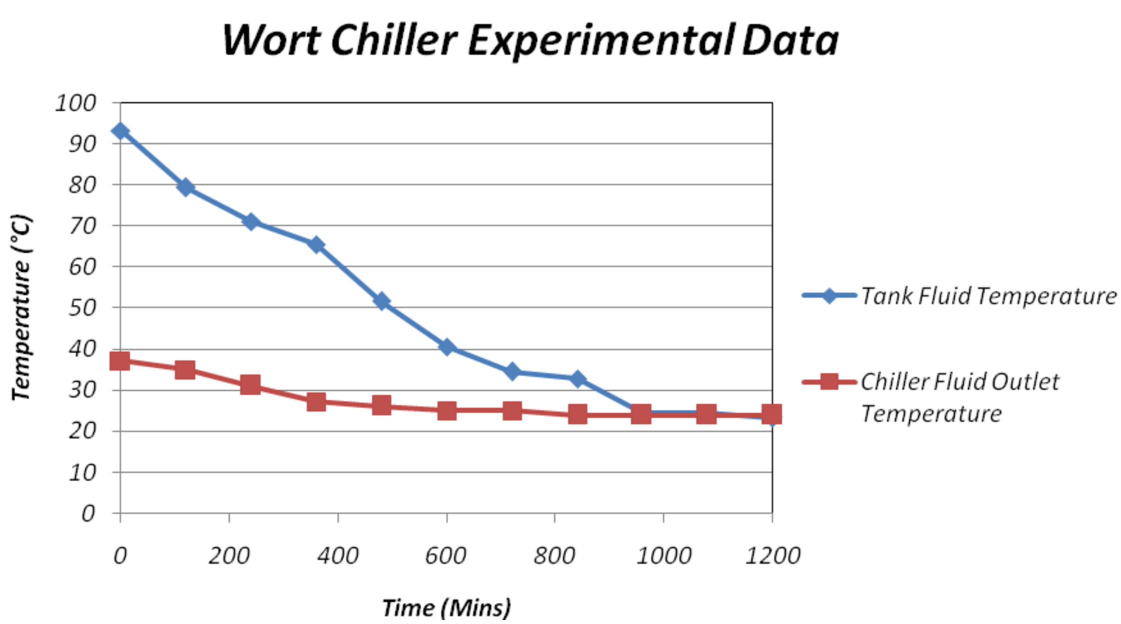



**Figure E-2.** Graph of temperature of water reservoir and chiller fluid outlet temperature over time

| Time (sec) | Water Temperature (C) | Chiller Outlet Temperature (C) |
|---|---|---|
| 0 | 93.33333333 | 37 |
| 120 | 79.44444444 | 35 |
| 240 | 71.11111111 | 31 |
| 360 | 65.55555556 | 27 |
| 480 | 51.66666667 | 26 |
| 600 | 40.55555556 | 25 |
| 720 | 34.44444444 | 25 |
| 840 | 32.77777778 | 24 |
| 960 | 24.44444444 | 24 |
| 1080 | 24.44444444 | 24 |
| 1200 | 23.33333333 | 24 |

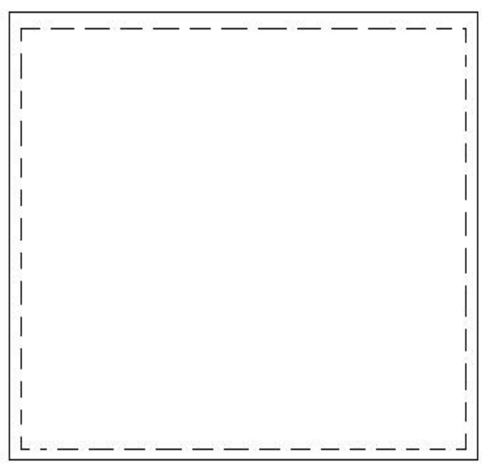
**Figure E-3.** Chart of Experimental Wort Chiller Data.

**Analysis**

<u>Assumptions:</u>

1. Well Insulated
2. No Work Done to the System
3. No Change in Kinetic or Potential Energy
4. Constant Properties
5. Neglect Heat Transfer to Outside Environment

<u>Control Volume:</u>



| Constants | |
|---|---|
| Fluid: | Water |
| Volume: | 3gallons = 0.01136 m^3 |
| Inlet Water Temperature: | 15.6°C |
| Mass of Fluid: | 11.36 kg |
| Internal Energy: | u(T1)=u(93°C)=381.08 kJ/kg |
| | u(T2)=u(41°C)=171.736 kJ/kg |
| Time: | 600 seconds |

**Figure E-4.** Basic Control Volume and Constants used for wort chiller analysis.

Analysis:

$$\Delta KE + \Delta PE + \Delta U = Q + W$$

$$\Delta KE = \Delta PE = W = 0$$

$$\Delta U = Q$$

$$Q = m(u_2 - u_1)$$

$$Q = 11.36kg\left(171.736 - 381.08\frac{kJ}{kg}\right)$$

$$Q = -2378.148kJ$$

$$\dot{Q} = \frac{Q}{\Delta t}$$

$$\dot{Q} = \frac{-2378.148\ kJ}{600s}$$

$$\dot{Q} = -4kW$$

**Conclusion:**

From our calculations, the wort chiller that we have specified will be able to dissipate enough thermal energy to keep the system at a constant temperature. Modifications to flow rate and chiller fluid temperature will be needed until the proper amount of heat transfer is achieved. We recommend using 5 gallon wort chillers with the thermal testing fixture in order to keep a constant fluid temperature in the tanks and in order to recreate typical operating conditions when testing the each module cover design.