OPTIMIZATION OF A PARAFFIN COOLING SYSTEM FOR
AN AUTOMATED TISSUE EMBEDDING CENTER

A Thesis Presented to

The Faculty of the

Fritz J. and Dolores H. Russ
College of Engineering and Technology
Ohio University

In Partial Fulfillment
Of the Requirement for the Degree

Master of Science

by

Adam Landis
March, 2004
Acknowledgements

I would like to thank Dr Williams for all his help as I (at last) complete my graduate studies. I would also like to thank Tom Ward for employing me while I carried out this work.

I would also like to thank my parents for all the support and free food. To all my friends, thank you for reminding me that I need to take a little time to relax every once and a while.
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1. Introduction

1.1. Problem Statement

This project was undertaken in an effort to improve the performance of the AutoTEC tissue embedding center. The improvements this project will evaluate are limited to the base mold system, the system responsible for solidifying the paraffin by removing the heat from the liquid paraffin-filled sample cassettes.

The goals of this project were defined as follows:

- Develop a simple and repeatable method to solder base mold assemblies.
- Evaluate the performance of the soldered assemblies in comparison to the original design.
- Determine the increase in supplied voltage necessary to improve performance without drawing too much additional power.
- Evaluate the design of the existing heat sink to determine which modifications might improve performance.
- Simplify the manufacturing and assembly process for the base mold assemblies.

Prior to this project, the cycle time of the AutoTEC embedding center was limited by the time required for the cooling of the cassettes. Reducing the time required for this process will increase the total number of cassettes processed per minute. Any improvement in the rate at which the cassettes are processed will make the AutoTEC system more attractive to potential purchasers. Currently, a well-trained Histologist is
capable of embedding cassettes at a maximum rate of two per minute. It is hoped that final operational processing rate of the AutoTEC system will be above four cassettes per minute.

There are two ways to improve the rate of processing: Either the thermal resistance of the heat sink must be reduced, or performance of the thermal electric cooler must be increased, or both. Either method will result in a faster transfer of heat to the ambient air.

1.2. Proposed Solutions

There are several ways of solving the problems described in Section 1.1. It was decided that this project would explore both principal options. First, it will be attempted to change the junction of the thermoelectric cooler (TEC) from a system using paraffin coated aluminum pads to one which is soldered. This will both reduce the thermal resistance of the junction and simplify the assembly process.

Changing the interface will require the development of a procedure for the soldering of the TEC module. The modules themselves are very delicate and require special care to avoid damage during the soldering process.

Increasing the supply voltage to the TEC will also be evaluated. Simply put, increasing the supplied power will increase the modules' performance. However, the increase in supplied power will also result in an increase in required input power as well as generated heat; it will also entail costs in re-designing the electronics which control the function of the TEC modules.
The design of the heat sink will be evaluated in order to determine what, if any, improvements can be made. This evaluation will be based on an analytical model and finite element analysis.

1.3. Literature Review

Literature research was conducted primarily on the processes and phenomena involved in thermoelectric cooling, and involved research into the materials used in the construction of thermoelectric devices as well as the design of the modules. Additional investigation was performed on heat sink design and analysis.

1.3.1. Thermoelectric Evaluation and Applications

The field of Thermoelectrics began with Seebeck’s discovery that a continuous flow of electric current could be created by forming a closed-circuit composed of a junction of two metallic compounds [1821]. This phenomenon occurs in response to a temperature change to which the junctions are exposed. It is through the Seebeck effect that thermocouples function.

In investigating the Seebeck effect, Peltier found that heat could be transferred between the dissimilar metallic junctions when electric current is supplied to the junctions. This phenomenon forms the basis of thermoelectric cooling.

Barnard [1972] describes the basic process involved in thermoelectric device operation. He describes both the Seebeck and Peltier effects in detail. The Peltier effect is described as a bulk property of the two metallic materials, not a contact phenomenon arising from the electromotive force (E.M.F) developed at the junction. The Peltier coefficient for the two materials is defined by (1-1).
\[ \Pi_{AB} = \frac{(\Delta I_u)_{AB}}{I} = \frac{1}{e} \left( \overline{E}_A - \overline{E}_B \right) \] (1-1)

The Peltier coefficient depends solely on the temperature difference. The heat that is absorbed is not equal to that which is rejected, except for cases where the junctions are at the same temperature.

The thermal and electrical properties of the semiconductor alloys used in the design of thermoelectric devices are described by Smith [1921]. Smith describes many combinations of thermoelectrically active alloys. Of particular interest is the alloy composed of the combination of Bismuth and Tellurium. This is the alloy commonly used in today’s semi-conductors. According to Smith, the thermoelectric conductivity of Bismuth-Telluride is greatest with a Tellurium concentration of approximately 50%.

Smith also discusses the magnetic and electric conductivity of the compounds.

The thermoelectric capacity of the Bismuth-Telluride semi-conductors was evaluated by Tashiro, Yonetsu, Matsuo and Takagi [1999]. They concluded that the smaller-grained material has higher heat pumping capacity.

In *Thermoelectric Properties of Semiconductors*, Kutasov, Pomazanov and Tikhomirov [1964] discuss combining the thermoelectric junctions in series, increasing the heat transfer properties. A thermoelectric generator composed of two semiconductor plates will produce maximum efficiency when the temperature difference between the plates is on the order of several hundred degrees Celsius. By using multiple thermocouple junctions, the temperature difference required for the optimum performance of the generator can be reduced. Cooling devices for different scientific applications are discussed by Kolenko [in Kutasov, 1964, pp 77-78].
The performance modeling of the thermoelectric modules is described in detail by Melcor, on their web site. The complete modeling equations are described and provided for determining the behavior of the thermoelectric modules. The calculations concerning the module coefficient of performance are particularly important, together with those concerning the determination of the heat transferred at the cold side. Melcor supplies additional information about the mounting of thermoelectric modules, and the operation of both thermoelectric coolers and generators.

Also available from Melcor is software designed for the simplification of the module analysis. The performance analysis of the modules manufactured by Melcor can be performed using the supplied Aztec® software. The software is limited to those manufactured by Melcor, but nonetheless it provides useful information.

The design of thermoelectric cooling devices is described by Goldsmid [1964], who describes the design of an ideal unit as well as that of a non-ideal one in practical application. An ideal thermoelectric cooling device is defined by Goldsmid as one which does not have any resistance across the module leads. The primary focus is on the design of non-ideal units which are practical for production and usage.

Methods for thermoelectric module evaluation are also described by Gorodetskiy, who discusses the determination of module resistance and the figure of merit which are used to define the quality of the thermoelectric module. The determination of the figure of merit and resistance are presented using the Harman method. The equations used for this calculation are shown in (1-2) and (1-3) for the resistance and figure of merit respectively:
Gorodetskiy presents methods for the simplification of the Harman method which correspond to the equations presented on the Melcor website. Further details on thermoelectric performance modeling are discussed by Semenyuk, Stockholm and Gerard [1999]. This discussion focuses on the thermoelectric device as well as the heat source and sink.

Moores, Joshi and Miller [1999] describe performance assessment methods for the evaluation of high temperature thermoelectric coolers. Whereas previous modules were limited to temperature differences of less than 100°C, progress in thermoelectric materials now makes it possible for temperature differences between the hot and cold surfaces of over 200°C.

To test the modules, an apparatus consisting of a high temperature thermoelectric cooler mounted to a heat sink. The cold side of the thermoelectric cooler is insulated by means of silicone insulating material. The test was performed at an ambient temperature of 176°C yielding a hot side temperature of 190°C.

The applications of thermoelectric devices are discussed by Chu and Simons [1999]. Their primary focus is the use of such devices in cooling computer systems. A more detailed description of thermoelectric applications is offered by Dubois [1999], who discusses military applications such as cooling of infrared detectors and microprocessors. Dubois also discusses their uses in commercial designs such as refrigeration in portable coolers and for the cooling of electronics devices.

\[ R = \frac{U_i - U_s}{I} \quad (1-2). \]

\[ Z = \frac{1}{T_a} \cdot \frac{U_s}{U_i - U_s} \quad (1-3). \]
1.3.2. Heat Sink Analysis

The heat transfer analysis was performed primarily with reference to the work of Incropera and Dewitt [2002]. They describe in detail the many processes in which heat transfer occurs are described, and give many examples for clarification.

Modeling methods for determining the forced air flow through ducts is described by Shah and London [1978]. Since the heat sink used in the design of the AutoTEC system has ducts which are fully enclosed, Shah’s methods are particularly useful in the current analysis. The methods presented by Shah and London focus on laminar flow through the duct.

Scott [1974] describes methods used for the cooling of electronic devices. As modern electronics become more complex and operate at higher speeds, more heat dissipation is required. Scott describes the common processes used in the dissipation of heat energy. Of particular interest to this project is the use of forced air convection. Scott discusses the effects of heat sink geometry. The use of thermoelectric coolers in refrigeration is evaluated in detail.

In order to develop an accurate model of the hot side assembly, research into the calculation of spreading resistance through the surface of the heat sink was performed.

Thyrum [at the Thermacore web site] describes a proprietary method developed by Thermacore which uses a hollow heat sink with water vapor contained inside. As heat is transferred through the heat sink, the process of evaporation and condensation of the internal fluid causes an even distribution of heat throughout the body of the heat sink.
A useful model for the determination of spreading resistance through the heat sink was supplied by Song and Lee [1994] and Lee and Moran [1995]. The spreading resistance caused by the geometry difference between the heat source and heat sink is an important factor which must be accounted for in modern electronics cooling. The models presented by Lee and Song were thorough and complex. A simplified version of the methods presented in the works cited above was presented by Lee [1998], and this is the method used to evaluate the heat sink used in the AutoTEC embedding center.
2. Background

As the Introduction notes, this project was undertaken in order to improve the performance of the paraffin cooling system of the AutoTEC paraffin embedding center. This machine uses many systems and processes to automate the task of tissue embedding. Section 2.1 describes the histology process, which the AutoTEC embedding center is designed to improve. The AutoTEC system is described in detail in section 2.2. Section 2.3 describes the base mold system that will be modified in an attempt to improve the system performance. Finally, section 2.4 describes the operation of the Thermal Electric Coolers.

Specific details about the machine design and components are not presented, due to a confidentiality agreement with Ward Engineering. The information presented describes the system with sufficient detail without infringing upon the confidentiality agreement.

2.1. Histology Process

The AutoTEC automated embedding center was designed to reduce the time required for the embedding portion of the Histology process.

Histology, defined as the process of preparing biological tissue samples for clinical analysis (Mahon, 2002), involves several steps. These steps will be discussed in the order in which they are performed.
The first step is to section the tissue sample that has been surgically removed from the patient. Tissue is usually removed from the periphery of the tumor to ensure that the surface margins are tumor-free. Sampling tissue at the center of the tumor is not very useful since the tissue typically is severely necrotic and thus useless for analysis (Hruban, 1995). Otherwise, the tissue samples are evaluated to determine if it is malignant or benign. The margins of the tissue sample are stained with marking ink (Figure 2-1) prior to sectioning.

![Figure 2-1. Tissue Marking](image)

Once stained, the tissue is sectioned for analysis. The tissue is cut in the form of thin rectangular segments. Segments are cut from the healthy portion of the tissue sample, as well as the deformed portion of the sample. Figure 2-2 shows how the segments are removed.

![Figure 2-2. Tissue Sectioning](image)

The sectioned tissue segments are then placed into pre-labeled cassettes, specifically designed for use in the AutoTEC embedding center. Before the tissue can be placed into the cassette, however, the cassette itself must be fitted into a plastic
frame. The frame is labeled for tracking purposes. The AutoTEC system grips the frame so that the tissue sample may be transferred through the various machine operations. The cassette snaps into the frame, and is held into place by small tabs within the frame.

Figure 2-3 shows a cassette being inserted into a frame.

![Figure 2-3. Cassette Insertion into Frame](image1)

The tissue sample is then carefully placed inside of the cassette. The orientation of the sample is important - the sample must be aligned with the long axis of the frame, as shown in Figure 2-4.

![Figure 2-4. Tissue Placement](image2)

The lid of the cassette is then snapped into place, holding the tissue inside the cassette. The sample is now ready for the next step, fixation. The goal of fixation is to preserve the tissue structure and cellular details.
After fixation, water must be removed from the tissue. The tissue is placed in a series of baths of denatured alcohol (Figure 2-5), each one at a higher concentration. This process removes all water from the sample. Once dehydration is complete, the sample is bathed in xylene in order to remove the alcohol for the sample.

After the alcohol has been removed from the tissue by xylene, the sample must be infiltrated with liquid paraffin in order to complete the processing. Once the tissue preparation is complete, embedding can begin.

The manual embedding process is performed by first placing the frame and cassette into a stainless steel base mold. The cassette is then pressed downward into the base mold with a specifically designed tamping device (Figure 2-6). The tamping device presses the Paraform cassette into the proper position within the base mold.
The base mold and sample cassette are heated to approximately 60 to 65°C. Liquid paraffin is then poured into the base mold (Figure 2-7) until the tissue sample held within the cassette is completely encased.

Once the liquid paraffin has been dispensed into the frame and base mold, it is then placed on a cold plate until it reaches a final temperature of approximately 0°C. When the paraffin reaches this temperature, it begins to release from the base mold, and the embedded block is easy to remove.

At this point the embedded sample is ready for sectioning, which is performed on a microtome. The base of the cassette is trimmed using a thickness setting of 50μ. Once the bottom of the Paraform cassette has been removed through trimming, the
microtome thickness setting is reduced in order to produce very thin samples at 3-4μ for analysis. Figure 2-8 shows a cassette being trimmed in a microtome machine.

Figure 2-8. Cassette Trimming

The microtome produces a thin ribbon of slices from the sample cassette. These ribbons are floated out on a bath of water, which is set to 54°C. In Figure 2-9, the sides of the Paraform cassette are visible surrounding the tissue. The thin sample ribbon is then placed onto a microscope slide, where it is dried and stained for analysis.

Figure 2-9. Sample Ribbon
2.2. **AutoTEC Description**

The AutoTEC tissue embedding center reduces the time required for the completion of the Histology process described in Section 2.1. In conjunction with the TissueTEK rapid tissue processor, the AutoTEC is intended to automate the process of tissue embedding. Many steps once required to be performed by lab technicians can be performed faster and with fewer errors. Figure 2-10 shows the front of the AutoTEC system.

![AutoTEC, Front View](image)

**Figure 2-10. AutoTEC, Front View**

Prior to embedding in the AutoTEC, the tissue samples are prepared in the rapid tissue processor, which carries out the fixation and dehydration stages of the process.

Frame-mounted cassettes are put into the AutoTEC in magazines. The AutoTEC's robotic systems move each cassette from its input magazine to a base mold and then, after embedding, place it in an output door. Once an output door is full, it is removed by a technician, and replaced with an empty one.
While the cassette and frame are in a base mold, a robotic assembly called the stager presses down on the cassette to put it in the proper position within the frame and base mold. The stager then dispenses liquid paraffin into the base mold.

After it is placed in the base mold, the stager presses the frame down on the base mold, and then pushes the cassette down into the base mold well. The base mold is heated for thirty seconds to a temperature of approximately 65°C. After the thirty seconds of heating, the stager dispenses paraffin into the base mold well, embedding the tissue sample and the cassette which holds it.

After the paraffin is dispensed, the base mold is switched from heating to cooling. The base mold is cooled for 210 seconds, after which the paraffin block has reached a final temperature of between 0 and 4°C. When the paraffin has reached this temperature, it is a solid block that separates from the walls of the base mold; at this point, the block and its frame are easily removed.
The tissue sample is removed from the base mold and put into an output door. The placement of the finished cassette into the output basket is done sequentially – the system's computer tracks which positions in the output baskets have been filled, and places each cassette into the next open position. Figure 2-11 shows embedded cassettes in an output door.

![Figure 2-11. A Full Output Door](image)
Once the output baskets are full, they are removed from the AutoTEC center. The embedded cassettes are then removed from the output baskets in order for the sectioning process to be completed. Fully embedded cassettes are shown in Figure 2-12.

![Embedded Cassettes](image)

Figure 2-12. Embedded Cassettes

Using the input magazines, the AutoTEC system can be continuously operated, with stoppages only for the refilling of the input door. The paraffin reservoir is refillable with either liquid or solid paraffin flakes while the machine is in operation. The reservoir level is monitored to ensure that the machine does not run out of paraffin.
2.3. Base Mold Description

The base mold system is where the tissue embedding takes place. It is therefore central to the performance of the AutoTEC system. The base mold assembly comprises three main components. First is the base mold, the aluminum well into which the paraffin is dispensed and where it is cooled. Second is the thermoelectric cooler (TEC), used for the bi-directional transfer of heat; the TEC is used for both the heating and cooling of the base mold. The final component is the heat sink, which accepts the heat transferred from the base mold and rejects it to the atmosphere. A Pro Engineer model of the base mold assembly is shown in Figure 2-13. The arrow denotes the direction of the airflow.

![Base Mold Solid Model, Showing Airflow](image-url)
The AutoTEC system has eight base mold assemblies which are used for the tissue embedding. Figure 2-14 shows an interior view of the AutoTEC system. The robotic assembly is visible inside the vertical box; the horizontal box indicates the array of base mold assemblies.

![AutoTEC, Interior View](image)

Each base mold assembly mounts two different base mold models. One is the standard large tissue base mold, while the other is the smaller biopsy base mold. The standard base mold is mounted to the heat sink at the end where the airflow exits. The biopsy base mold is mounted in the center of the heat sink.

Between the base mold and heat sink is the TEC. Interface pads made of paraffin coated aluminum are used to increase the surface area of contact between the surfaces of the aluminum components and the ceramic TEC surface. When heated, the paraffin melts and fills in the microscopic voids of the surfaces, thus increasing the contact area.
The TEC is located on the heat sink by means of a shallow pocket milled into the upper surface of the heat sink. The base mold is then located to the TEC and heat sink by two locating pins pressed in the heat sink. The base mold and TEC are then held in place by compressive force supplied by four toe clamps. The toe clamps are tightened using a digital torque meter. The mounting of the base mold can be clearly seen in Figure 2-15. Shown in the figure is a close up of an assembly with both biopsy and standard base molds held in place with toe clamps.

Figure 2-15. Base Molds, Close Up

To maintain control of the TEC, a resistive thermal diode (RTD) is mounted to the flat shelf of the base mold. The RTD is held in place by means of a sheet metal strap which is fastened to the base mold by screws. The RTD gives temperature feedback to the TEC controller board that controls the cycling of the assemblies.
The heat sink absorbs the heat pumped from the base mold by the TEC. The heat sink then rejects the heat to the ambient air. The heat sink used in the base mold assembly is an aluminum extrusion with ten internal air passageways. The air passages can be seen in Figure 2-17.

Figure 2-16. Heat Sink, End View

Air flow is forced through the heat sink by two brushless fans. Each side of the heat sink uses a plenum to allow the airflow to fully develop before entering the heat sink. The plenums and fans mount to the four tapped holes on the end of the heat sink shown in Figure 2-16. The fans move air through the heat sink at an average velocity of 5m/s.
2.4. Thermal Electric Cooler Operation

Thermal electric coolers are solid-state electrical devices. Thermoelectricity occurs due two principles, named for their early nineteenth century discoverers - the Seebeck Effect and the Peltier Effect.

Seebeck found that a continuous current would flow in a closed circuit composed of dissimilar metals if the junctions of the two metals were held at different temperatures; (Buist, 1997). The Seebeck Effect is illustrated in Figure 2-17.

![Figure 2-17. Seebeck Effect](image)

The Seebeck Effect occurs when a junction of two dissimilar metals is exposed to a temperature difference. In response to the temperature difference, a current is induced by the metallic junction. This current is proportional to the temperature difference which the junctions are exposed.

Thermocouples operate based on the Seebeck Effect. Thermocouples are junctions of dissimilar metals which are used to determine temperature. The current magnitude is measured in order to determine what the temperature at the metallic junction is.
Virtually any combination of metals can be used for creating a thermocouple. However, some combinations are particularly efficient when combined. Table 2-1 shows the most common of these metallic combinations:

Table 2-1. Thermocouple Junction Combinations

<table>
<thead>
<tr>
<th>Name</th>
<th>Metal 1</th>
<th>Metal 2</th>
<th>Temp. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>J Type</td>
<td>Iron</td>
<td>Copper-Nickel</td>
<td>0 - 750°C</td>
</tr>
<tr>
<td>K Type</td>
<td>Nickel-Chromium</td>
<td>Nickel-Aluminum</td>
<td>(-)270 - 1370°C</td>
</tr>
<tr>
<td>T Type</td>
<td>Copper</td>
<td>Copper-Nickel</td>
<td>(-)270 - 400°C</td>
</tr>
</tbody>
</table>

It was pointed out in the Introduction that the Peltier Effect is essentially the opposite of the Seebeck Effect. Peltier found that thermal energy could be transferred between the metal junctions by applying a current within the closed circuit (Buist and Lau, 1997). The Peltier effect is a bulk property of the two metallic materials, not a contact phenomenon arising from the electromotive force developed at the junction (Smith, 1921).
Thermal electric coolers function based on the Peltier Effect. The amount of heat transfer the module can produce is controlled by the amount of current supplied to the module. The direction of the heat flow is dependent on the direction of the supplied current. The basic configuration of a thermoelectric cooler is shown in Figure 2-18.

![Thermal Electric Cooler Diagram](image)

Figure 2-18. Thermal Electric Cooler Diagram (Buist and Lau, 1997)

Instead of a junction formed by the combination of standard metals, the thermoelectric junctions used in a TEC are made of two elements of a semiconductor. A typical semiconductor used is Bismuth Telluride. The semiconductor is heavily doped to create an excess of electrons (N-type) or a deficiency of electrons (P-type). The N and P type semiconductors are combined electrically in series and thermally in parallel so that heat flows from surface to surface (Buist and Lau, op. cit.). The N type semiconductor possesses an excess of electrons within its molecular lattice. The P type semiconductor possesses a deficiency of electrons within its molecular lattice. The combination of electron excess and electron deficiency is responsible for the heat flow.

The flow of electrons caused by the supplied power is used to transfer the heat from a heat source to a heat sink. At the cold junction, heat is absorbed from the heat
source as electrons move from a lower energy state at the P-type conductor to a higher energy state at the N-type conductor. The heat is then rejected to the heat sink as the electrons are forced to a lower energy level when they move to the P-type conductor.

The thermocouple junctions are bonded to ceramic plates made of alumina oxide. The surfaces of the ceramic plates form the interface between the heat sink and base mold. To improve the heat transfer between the aluminum and ceramic surfaces, it is necessary to use an interface material. Typical interfaces used are thermal grease, solder, and paraffin/aluminum pads. The junction materials increase the thermal conductivity by filling gaps and microscopic voids between the two surfaces.

Each interface type has its advantages and disadvantages. Thermal grease is easy to apply to surfaces, but is messy. Solder is the best thermal conductor of the interfaces, but is very rigid and susceptible to damage due to thermal expansion. The interface pads are easy to apply but have a lower thermal conductivity.

A typical thermoelectric cooler is shown in . The module pictured is manufactured by Melcor.

---

Figure 2-19. Thermoelectric Cooler
Many commercial manufacturers of thermoelectric coolers exist. Two of the better-known companies are Melcor and Marlow. The thermoelectric coolers used in the AutoTEC embedding center are all manufactured by Melcor. This choice was based on reliability testing and usage history during the early system development.

The current TEC used in the design of the AutoTEC system is the Melcor HT8-12-40. This is a high temperature module, capable of temperatures of 212°C. Most TEC modules are limited to a maximum temperature of around 80-90°C. The model HT8-12-40 has 127 thermocouple connections and is 40mm wide x 44mm long by 3.5mm thick. This module is capable of a temperature difference of up to 70°C between the two faces. At the maximum supply voltage of 14.4 VDC, the TEC is capable of transferring 70W of heat.
3. **Modeling**

Performance modeling was performed using simplified thermal resistance models of the specific components. This simplified modeling was carried out in order to reduce the time required in the analysis. The performance of a simple liquid-cooled heat sink was also evaluated.

3.1. **Cold Side Thermal Modeling**

A thermal resistance model was developed to describe the behavior of the cold side of the base mold assembly. This resistance model would later be used to determine the ideal amount of energy which could be transferred from the cold side by the thermal electric cooler. The cold side of the base mold assembly is shown in Figure 3-1.

![Figure 3-1. Cold Side Components](image)

The cold side thermal resistance model was developed based upon several assumptions in order to simplify the analysis. These assumptions describe the ideal
behavior of the assembly and represent the maximum performance of which the system is capable.

- The initial temperature of the cold side is assumed to be uniform at 62°C.
- The final temperature of the aluminum base mold is constant at 0°C.
- Heat loss to natural convection is assumed to be negligible.
- The final average temperature of the paraffin block is 10°C.
- The final temperature of the frame is 62°C.

The major components of the cold side resistance model are the frame, paraffin, and base mold. Initially, all three components are at a uniform temperature of 62°C. Due to the low thermal conductivity of the paraffin and frame, a temperature gradient exists. To simplify the gradient, the average temperature of the components was used for the modeling.

The thermal resistance model was derived in a top-down manner. In order for the heat to be removed by the thermal electric cooler, it must flow from the frame and paraffin through the base mold. Heat is then absorbed by the upper surface of the thermal electric cooler.

Figure 3-2 shows the thermal resistance model developed for the cold side of the base mold assembly.
Figure 3-2. Thermal Resistance Model

The thermal resistance model was created assuming that the paraffin is thermally in parallel with the frame and base mold side walls. The bottom of the frame rests upon the top of the base mold's side walls. The liquid paraffin is then dispensed into the well formed by the base mold and frame. Therefore, the thermal resistance model shown in Figure 3.2 is a reasonable approximation of the behavior of the base mold cold side. The relevant characteristics are listed in Tables 3-1, 3-2 and 3-3.

Table 3-1. Frame Dimensions

<table>
<thead>
<tr>
<th>Frame Dimension</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Length</td>
<td>0.035</td>
<td>m</td>
</tr>
<tr>
<td>Outside Width</td>
<td>0.028</td>
<td>m</td>
</tr>
<tr>
<td>Inside Length</td>
<td>0.031</td>
<td>m</td>
</tr>
<tr>
<td>Inside Width</td>
<td>0.025</td>
<td>m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.025</td>
<td>m</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.23</td>
<td>W/mK</td>
</tr>
</tbody>
</table>

Table 3-2. Paraffin Block Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, Paraffin</td>
<td>0.031</td>
<td>m</td>
</tr>
<tr>
<td>Width, Paraffin</td>
<td>0.025</td>
<td>m</td>
</tr>
<tr>
<td>Thickness, Paraffin</td>
<td>0.0035</td>
<td>m</td>
</tr>
<tr>
<td>Solid Conductivity</td>
<td>0.24</td>
<td>W/mK</td>
</tr>
<tr>
<td>Liquid Conductivity</td>
<td>0.5</td>
<td>W/mK</td>
</tr>
</tbody>
</table>
Table 3-3. Base Mold Properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Length</td>
<td>$l_b$</td>
<td>0.04</td>
<td>m</td>
</tr>
<tr>
<td>Base Width</td>
<td>$w_f$</td>
<td>0.044</td>
<td>m</td>
</tr>
<tr>
<td>Base Thickness</td>
<td>$t_b$</td>
<td>0.0005</td>
<td>m</td>
</tr>
<tr>
<td>Wall Outside Width</td>
<td>$w_{w,o}$</td>
<td>0.028</td>
<td>m</td>
</tr>
<tr>
<td>Wall Outside Length</td>
<td>$l_{w,o}$</td>
<td>0.035</td>
<td>m</td>
</tr>
<tr>
<td>Wall Inside Width</td>
<td>$w_{w,i}$</td>
<td>0.267</td>
<td>m</td>
</tr>
<tr>
<td>Wall Inside Length</td>
<td>$l_{w,i}$</td>
<td>0.034</td>
<td>m</td>
</tr>
<tr>
<td>Wall Height</td>
<td>$t_w$</td>
<td>0.0047</td>
<td>m</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$K_{cm}$</td>
<td>150</td>
<td>W/mK</td>
</tr>
</tbody>
</table>

The first step in the cold side modeling was the calculation of the thermal resistance for the frame. The frame like the solid paraffin has a poor thermal conductivity. The frame is made of Acetyl, and has a conductivity of 0.23 W/m-K. The thermal resistance of the frame was calculated using (3-1).

$$ R_{fr} = \frac{t_f}{k_{fr} \cdot A_{fr}} $$

(3-1)

In order to calculate the frame resistance, the area of the frame was determined.

$$ A_f = (l_{f,o} \cdot w_{f,o}) - (l_{f,i} \cdot w_{f,i}) $$

$$ A_f = (0.035m \cdot 0.028m) - (0.031m \cdot 0.025m) $$

(3-2)

$$ A_f = 0.00021m^2 $$

Based on (3.1), the thermal conductivity of the frame was calculated to be 124.4 K/W. This is a very large number, because of the small surface area of the part of the frame in contact with the base mold.

The thermal resistance of the paraffin block was calculated next. While the final temperature of the paraffin is non uniform, it does totally solidify. Therefore, the thermal resistance calculation was performed using the solid thermal conductivity of
0.24 K/W. The thermal resistance of the paraffin block was calculated using the same equation as the frame.

\[ R_p = \frac{L_p}{a_p \cdot K_p} \]  

(3-3).

Based on this calculation, the thermal resistance of the paraffin was determined to be 18.2 K/W. In similar fashion, the thermal resistance of the base mold walls and base mold surface were determined.

\[ R_{w,bm} = \frac{t_{w,bm}}{a_{w,bm} \cdot k_{bm}} \]  

(3-4).

\[ a_{w,bm} = (l_{w,o} \cdot w_{w,o}) - (l_{w,j} \cdot w_{w,j}) \]

\[ a_{w,bm} = (0.035m \cdot 0.028m) - (0.034m \cdot 0.0267m) \]

\[ a_{w,bm} = 0.0000722m^2 \]  

(3-5).

\[ R_{w,bm} = \frac{0.0047m}{(0.0000722m^2) \cdot 142W/m \cdot K} \]

\[ R_{w,bm} = 0.434K/W \]  

(3-4 Continued).

\[ R_{s,bm} = \frac{t_{bm}}{a_{bm} \cdot k_{6061}} \]

\[ R_{s,bm} = \frac{0.00005m}{(0.04m \cdot 0.044m) \cdot 150W/m \cdot K} \]

\[ R_{s,bm} = 0.00019K/W \]  

(3-6).
The overall cold side thermal resistance was then calculated according to 3.7.

\[
R_{CS} = \frac{1}{\frac{1}{R_{fr}} + \frac{1}{R_{w,bm}} + \frac{1}{R_p}}
\]

(3-7)

Based on Equation (3-7), the overall thermal resistance of the cold side was calculated to be 15.8 K/W. This is a high value which is due to the poor thermal conductivity of the cold side components.

3.2. Hot Side Thermal Modeling

As with the cold side, a thermal resistance model was developed to describe the behavior of the hot side. Heat is rejected from the base mold through the thermal electric cooler to the hot side. The hot side of the base mold assembly is composed solely of the heat sink.

The thermal resistance model for the base mold hot side was developed based on several assumptions to simplify the analysis.

- Heat lost to convection on the external surfaces is minimal.
- Heat transfer to the lower surface of the square heat sink extrusion is minimal.
- The velocity of the air flowing through the heat sink is constant at 5m/s.
- The ambient temperature of the environment remains constant at 22°C.
- The thermal electric cooler mounting surface remains at a constant temperature of 30°C.
- The model assumes one directional heat flow from the TEC mounting surface through the heat sink to the ambient air. The model is shown in Figure 3-3.
The heat flows from the thermal electric cooler first through the upper surface of the heat sink. Due to the geometry of the heat sink, spreading resistance occurs, adding to the resistance of the heat sink surface. Before being dissipated to the atmosphere, the heat energy must flow through the fin array. The fin array thermal resistance is a parallel combination of the conductive resistance of the fin material, and the resistance to the convective heat transfer to the air [Incropera, 2002].

The ideal system performance of the hot side was then calculated based on the thermal resistance model shown in Figure 3-3. This analysis was performed using the assumptions detailed above.

Since only one base mold is active at a time, the model was not evaluated at full size. The model used in the calculations as well as in the final FEA analysis was set at 2.5 inches long. This accounts for the TEC mounting surface and a half inch of material on either side. The first TEC is mounted a half inch from the end of the full sized heat
sink, and there is approximately one inch of space between the two base mold positions. The dimensions are listed in Tables 3-4, 3-5 and 3-6.

Table 3-4. Model 2401-11-051d Heat Sink Dimensions

<table>
<thead>
<tr>
<th>Base Thickness</th>
<th>t</th>
<th>0.00254</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Length</td>
<td>Lb</td>
<td>0.0635</td>
<td>m</td>
</tr>
<tr>
<td>Base Width</td>
<td>wb</td>
<td>0.0508</td>
<td>m</td>
</tr>
<tr>
<td>Base Area</td>
<td>ab</td>
<td>0.00323</td>
<td>m²</td>
</tr>
<tr>
<td>Fin Length</td>
<td>l</td>
<td>0.04676</td>
<td>m</td>
</tr>
<tr>
<td>Fin Width</td>
<td>w</td>
<td>0.001524</td>
<td>m</td>
</tr>
<tr>
<td>Fin Gap</td>
<td>g</td>
<td>0.003404</td>
<td>m</td>
</tr>
<tr>
<td># of fins</td>
<td>N</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-5. Material Properties

<table>
<thead>
<tr>
<th>Conductivity 6063 Alum.</th>
<th>k</th>
<th>160</th>
<th>W/mK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of Air</td>
<td>ρ</td>
<td>1.161</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Kinematic Viscosity, air</td>
<td>μa</td>
<td>2.08E-05</td>
<td>N-s/m²</td>
</tr>
<tr>
<td>Prandtl Number</td>
<td>Pr</td>
<td>0.707</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-6. State Properties

<table>
<thead>
<tr>
<th>Hot Temperature</th>
<th>T</th>
<th>335</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature</td>
<td>Tc</td>
<td>295</td>
<td>K</td>
</tr>
<tr>
<td>Air Velocity</td>
<td>U</td>
<td>5</td>
<td>m/s</td>
</tr>
</tbody>
</table>

The first step in the modeling of the hot side was the determination of the convection coefficient of the air forced through the heat sink. Since there are multiple fluid passageways, it was necessary to determine the flow characteristics for a single passageway. Ideally, the flow through the other passageways will be identical to that calculated for the single passageway.

Since the air flows through a non-circular duct, it was necessary to first calculate the hydraulic diameter. The hydraulic diameter is the equivalent circular duct which describes the flow through the non circular duct, thus simplifying the calculations. The hydraulic diameter was calculated through (3.8).
\[
D_h = \frac{4 \cdot a_c}{2 \cdot P}
\]
\[
D_h = \frac{4 \cdot (g_f \cdot l_f)}{2 \cdot (g_f + l_f)}
\]
\[
D_h = \frac{4 \cdot (0.0034m \cdot 0.0476m)}{2 \cdot (0.0034m + 0.0476m)}
\]
\[
D_h = 0.00635m
\]

Where \( A_c \) is the cross sectional area of the fin, and \( P \) is the perimeter exposed to the fluid flow.

The Reynolds number describing the flow was calculated for the flow through the passageway. If Reynolds number is less than or equal to 2300, flow is considered laminar.

\[
RE = \frac{\rho \cdot u_m \cdot D_h}{\mu_f}
\]
\[
RE = \frac{1.61 \frac{g}{kg^3} \cdot \frac{5 \text{ m}}{\text{s}} \cdot 0.00635m}{2.08 \cdot 10^{-5} \frac{N \cdot \text{s}}{m^2}}
\]
\[
RE = 1769.2
\]

Since the Reynolds number was calculated to be below 2300, flow is laminar through the passageway. The length to width ratio for the duct was calculated in order to approximate the Nusselt number.

\[
\frac{B}{A} = \frac{l_f}{g_f}
\]

Referring to Table 8.1, page 464 of Incropera's *Introduction to Heat Transfer* [2002], for a \((b/a)\) ratio of 13.9, the Nusselt number was determined to be 8.23. The convection coefficient was determined using (3-11).
Using (3-11), the convection rate of heat transfer in the duct was calculated to be 38.9 W/m²·K.

Once the convection coefficient was calculated, it was possible to determine the efficiency of the fin array. To do this, it was first necessary to determine the efficiency of a single fin.

\[ h = \frac{k_{\text{air}} \cdot Nu}{D_h} \]  

(3-11).

\[ m = \frac{h \cdot P}{K_h \cdot A_c} \]

(3-13),

\[ m = \sqrt{\frac{38.88W}{m^2 K} \cdot 2(0.0635m \cdot 0.0015m)} \]

\[ m = 18.1 \]

\[ \eta_f = \frac{Tanh(18.1 \cdot 0.047m)}{18.1 \cdot 0.047m} \]

\[ \eta_f = 0.814 \]

(3-12 Continued).

The efficiency of a single fin was determined to be 81.4%. The overall efficiency of the fin array is dependent upon the ratio of the area of a single fin to that of the total fin array. The surface area of a single is defined by Equation 3.14 while the surface area of the fin array is defined by Equation 3.15.
The total surface area of the fin array was calculated to be 0.061 m² while the area of a single fin was calculated to be 0.0059 m². Due to the increased surface area, the efficiency of the fin array is higher than that of a single fin. Equation (3.16) was used to calculate the overall fin array efficiency.

\[
\eta_o = 1 - \frac{N \cdot A_f}{A_{surf}} \cdot (1 - \eta_f)
\]

\[
\eta_o = \left(1 - \frac{10 \cdot 0.0059 m^2}{0.061 m^2}\right) \cdot 0.814
\]

\[
\eta_o = 0.819
\]

The efficiency of the array did increase slightly over that of the single fin. The overall efficiency of the fin array was calculated to be 82.1%. The higher efficiency is due to the small increase in surface area due to the webbing between the fins.

Once the flow characteristics of the heat sink were determined, the thermal resistance of the heat sink was calculated. Following the thermal resistance model shown in Figure 3-3, the resistances were calculated in a top down manner.
The thermal resistance of the heat sink surface was calculated first. The thermal resistance of a one-dimensional system is defined by (3-17).

\[ R_{s,hs} = \frac{I_{s,hs}}{a_{s,hs} \cdot k_{6063}} \]

Here, \( a \) is the cross sectional area of the surface which the heat is flowing through, \( t \) is the thickness of the surface, and \( k \) is the thermal conductivity of the material.

To better approximate the heat transfer of the hot side, the spreading resistance due to the geometry difference between the base mold and heat sink was calculated. Spreading resistance occurs where heat flows from one region to another in different cross sectional area [Ferrotec, 2000]. Spreading resistance is a common problem in the design of heat sink systems. Most electronic devices are very small but produce large amounts of heat. This trend requires increasingly larger heat sinks to dissipate the heat.

The surface area of the base mold is 0.0018m², while the surface area of the reduced size heat sink model is 0.0032m². Since the upper surface through which the heat must spread is very thin, the spreading resistance is large. The spreading resistance was calculated using (3-18).

\[ R_s = \frac{\sqrt{a_{r,hs} - a_{r,bm}}}{k_{6063} \cdot \pi \cdot a_{r,hs} \cdot a_{r,bm}} \cdot \frac{\lambda \cdot k_{6063} \cdot a_{s,hs} \cdot R_{b,hs} + \tanh(\lambda \cdot t_{b,hs})}{1 + \lambda \cdot k_{6063} \cdot a_{r,hs} \cdot R_{b,hs} \cdot \tanh(\lambda \cdot t_b)} \]  

(3-18).
Here, \(a_{s,hs}\) is the surface area of the heat sink, \(a_{s,bm}\) is the surface area of the base mold, and the geometry factor (\(\lambda\)) being calculated to be 120.9. Using (3.19) the spreading resistance through the upper surface of the heat sink was calculated to be 0.0162 K/W. This is significant since the thermal resistance of the heat sink surface was calculated to be 0.005 K/W. Due to the thin material and large area difference, the thermal resistance due to the additional spreading resistance was 300% greater than that of the surface alone.

Once the thermal resistance of the heat sink surface was determined, the thermal resistance of the fin array was calculated. The resistance is dependant upon the convection coefficient which was calculated based on the flow through the heat sink. The thermal resistance was calculated using (3-20).

\[
R_{fo} = \frac{1}{h \cdot a_{surf} \cdot \eta_0}
\]  

(3-20).

Equation (3-21) was used to determine the thermal resistance of the fin array for the reduced size heat sink model; the resulting value was 0.515 K/W. Combining the thermal resistances, the overall calculated resistance was 0.531 K/W.

Using the calculated thermal resistance of 0.531 K/W and the stated temperature difference of 8°C, the maximum heat transfer which is possible through the heat sink was determined to be 13.2 W. This value is dependent upon the previously stated assumptions. Under actual operational conditions, the maximum heat transfer from
the heat sink will vary based upon environmental conditions as well as the supply voltage of the TEC.

**3.3. Re-Designed Heat Sink Analysis**

In similar fashion to the analysis performed in Section 3.2, the performance of the beta production heat sink was performed. The beta unit heat sink is larger than the original design, allowing it to dissipate more heat. The same modeling equations used in Section 3.2 were applied to the beta heat sink, with the component variables being changed to represent the new design. The dimension are shown in Table 3-7.

<table>
<thead>
<tr>
<th>Table 3-7. Model 2404-11-010 Heat Sink Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Base Thickness</td>
</tr>
<tr>
<td>Base Length</td>
</tr>
<tr>
<td>Base Width</td>
</tr>
<tr>
<td>Fin Length</td>
</tr>
<tr>
<td>Fin Width</td>
</tr>
<tr>
<td>Fin Gap</td>
</tr>
<tr>
<td># of fins</td>
</tr>
<tr>
<td>Fin Area</td>
</tr>
<tr>
<td>Total Heatsink Internal Area</td>
</tr>
<tr>
<td>Air Velocity</td>
</tr>
</tbody>
</table>

The hydraulic diameter of the fluid passageways was calculated using (3-8) to be 0.00938m. The Reynolds number for the flow through the heat sink was then determined to be 3663 using (3.9). Since the Reynolds number is greater than 2300, the flow through the heat sink is turbulent. Since the Nusselt number approximation made in Section 3.2 was for laminar flow, a different equation was used to determine the Nusselt number for the beta heat sink.
\[ Nu = 0.023 \cdot RE_d^{3/5} \cdot Pr^{0.4} \]

\[ Nu = 0.023 \cdot 3663^{3/5} \cdot 0.707^{0.4} \]

\[ Nu = 14.2 \] (3-21).

Substituting the Nusselt number calculated in (3-21) into (3-11), and changing the geometry variables to represent the beta design heat sink, the convection coefficient was calculated to be 45.45 W/m²K.

The thermal resistance of the beta heat sink was calculated to be significantly lower than the original design. The overall thermal resistance of the beta heat sink was determined to be 0.261 K/W. Due to the lower thermal resistance and increased air velocity, the maximum heat dissipation through the beta heat sink was calculated to be 27 W.

### 3.4. Thermoelectric Cooler Performance Modeling

The modeling of the thermoelectric cooler was performed using equations supplied by the manufacturer. The equations are available at the Melcor website, www.melcor.com.

The two most important factors determining the performance of a thermal electric cooler are the supply voltage to the TEC, and the ambient temperature of the environment. To simplify the analysis, several assumptions were made.

- The ambient temperature remains constant at 22°C.
- The supply voltage is constant at 5.8CV DC.
- The hot side surface temperature remains constant at 30°C.
- The cold side surface temperature remains constant at 0°C.
Based on these assumptions, the analysis of the thermoelectric cooler was performed for the model HT8-12-40 TEC. This analysis is also valid for the model CP1.4-127-045 t/t TEC. The two modules have the same dimensions and number of thermocouple junctions.

In order to determine the amount of heat which could be removed as well as the operational efficiency of the module, several state variables were calculated. These variables include the Seebeck voltage, the resistivity of the module, and the thermal conductivity of the module.

The determination of these state variables is shown in the Appendix. The system constants are shown in Table 3-8.

<table>
<thead>
<tr>
<th>Table 3-8. System Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{hot}} )</td>
</tr>
<tr>
<td>( T_{\text{cold}} )</td>
</tr>
<tr>
<td>( T_{\text{amb}} )</td>
</tr>
<tr>
<td>( V )</td>
</tr>
<tr>
<td>( G )</td>
</tr>
</tbody>
</table>

The first step in the TEC performance evaluation was the determination of the average temperature across the module.

\[
T_{\text{ave}} = \frac{T_{\text{hot}} - T_{\text{cold}}}{2} \\
T_{\text{ave}} = 287.14 \, K
\]  

(3-22)

It was then necessary to determine the module performance variables. The performance variables are a function of the average temperature. The first performance variable calculated was the Seebeck Voltage.
\[ a = (a_0 + a_1 \cdot T_{\text{ave}} + a_2 \cdot T_{\text{ave}}^2) \times 10^{-9} \]
\[ a_0 = \frac{22224.0}{K} \]
\[ a_1 = \frac{930.6}{K^2} \]
\[ a_2 = -\frac{0.9905}{K^3} \]

\[ a = \left[ \frac{22224.0}{K} + \frac{930.6}{K^2} \cdot 287.14K + -\frac{0.9905}{K^3} \cdot (287.14K)^2 \right] \times 10^{-9} \]
\[ a = 0.00021 \frac{1}{K} \]

(3-23).

The module resistivity and thermal conductivity were then calculated.

\[ p = \left( p_0 + p_1 \cdot T_{\text{ave}} + p_2 \cdot T_{\text{ave}}^2 \right) \times 10^{-8} \]
\[ p_0 = 5112.0 \Omega \cdot \text{cm} \]
\[ p_1 = \frac{163.4 \Omega \cdot \text{cm}}{K} \]
\[ p_2 = \frac{0.6279 \Omega \cdot \text{cm}}{K^2} \]

\[ p = \left( 5112 \Omega \cdot \text{cm} + 163.4 \frac{\Omega \cdot \text{cm}}{K} \cdot 287.14K + 0.6279 \frac{\Omega \cdot \text{cm}}{K^2} \cdot (287.14K)^2 \right) \times 10^{-8} \]
\[ p = 0.00104 \Omega \cdot \text{cm} \]
\[ k = \left( k_0 + k_1 \cdot T_{ave} + k_2 \cdot T_{ave}^2 \right) \times 10^{-6} \]

\[ k_0 = \frac{62605.0}{cm \cdot K} \]
\[ k_1 = \frac{-277.7}{cm \cdot K^2} \]
\[ k_2 = \frac{0.4131}{cm \cdot K^3} \]

\[ k = \left( \frac{62605}{cm \cdot K} - \frac{277.7}{cm \cdot K^2} \cdot \frac{287.14}{K} + \frac{0.4131}{cm \cdot K^3} \right) \times 10^{-6} \]

\[ k = \frac{0.01693}{cm \cdot K} \]

The final performance variable calculated was the Figure of Merit.

\[ Z = \frac{a^2}{p \cdot k} \]

\[ Z = \frac{(0.00021/V/K)^2}{0.00104 \cdot \Omega \cdot cm \cdot \frac{0.01693}{W/cm \cdot K}} \]

\[ Z = 0.00246 \frac{1}{K} \]

Once the state variables were calculated, it was then possible to determine the ideal operating current for a supply voltage of 5.8V DC. The voltage draw as a function of the supply current is defined in (3-27).

\[ V = 2 \cdot N \left[ \frac{I \cdot p}{G} + a \cdot \Delta T \right] \]  

(3-27)

Where \( n \) is the number of thermocouple junctions in the TEC module (127 for both the model HT8-12-40 and the model CP1.4-127-045 t/t). The geometry factor \( g \) is defined as 0.171 for both modules, while the temperature difference between the hot and cold sides is defined as 30K. To determine the current draw as a function of the supply voltage, it was necessary to re-arrange the equation as shown in (3-27), in order to solve for the current.
Based on (3-28), the current draw of the module was calculated as being \(2.72\text{A}\). This value is slightly lower than the current measured during experimentation. During the continuous testing of the base mold assembly described in Chapter 5, an average current draw of \(2.93\text{A}\) was measured.

The heat pumped at the cold side of the thermal electric cooler was then calculated based on the current draw determined through (3-28). The equation for the heat pumped at the cold side is shown in (3-29).

\[
I = \frac{G \cdot \left[ \frac{V}{2 \cdot N} - a \cdot \Delta T \right]}{0.171 \cdot \frac{2.80\text{A} \cdot 273\text{K} - (2.72\text{A})^2}{2 \cdot 0.00104\Omega \cdot cm} - 0.00021V/K \cdot (303\text{K} - 273\text{K})}
\]

\(I = 2.72\text{A}\)

Based on (3-29), the ideal heat pumped at the cold side was calculated to be \(11.9\text{W}\). In comparison, at the average experimental operating current, the heat pumped at the cold side would be \(14.0\text{W}\).
The coefficient of performance for the TEC was then calculated in order to determine the efficiency of the module.

\[
COP = \frac{Q_c}{I \cdot V}
\]

\[
COP = \frac{11.87W}{2.72A \cdot 5.8V} = 0.753
\]

Based on (3-30), the coefficient of performance for the module using the current draw calculated in ((3-28) was determined to be 75.3%. The coefficient of performance relates the amount of heat transfer to the supplied power.

Experiments were performed to determine the performance of the system due to an increased supply voltage. The experimental results are given in Chapter 5. Based on the experimental results, it was decided to change the supply voltage to 7.0V. To verify the results measured in the experiment, the modeling of the TEC was redone for the new supply voltage of 7.0V.

Using (3-28) for a supply voltage of 7.0V, the ideal operating current was calculated to be 3.53 amps, while the heat pumped at the cold side was calculated to be approximately 20 W.

The calculated current draw matches up well with the experimentally interpolated value of 3.50 amps. Data trials were not performed at 7.0 V during the testing but rather at 6.8 and 7.3 V. This was because at the time of the testing, the voltage setting which the controller board was designed for was not known. The testing was performed in 0.5V increments of the normal set point of 5.8V.
3.5. Liquid Cooled Heat Sink Analysis

One possible solution to improving the heat removal from the base mold is the use of a liquid-cooled heat sink. Water has four times the thermal conductivity of air, which means that more heat can be removed from the base mold using a liquid cooled-heat sink, even one with smaller surface area of fluid contact.

Operating with the entire upper surface of the model 2404-13-011 heat sink at 30°C and the ambient air at a constant temperature of 22°C, a maximum of 28 W of heat transfer is possible. Under the same conditions using water as a working fluid, 376 W of heat transfer is possible. However, with the existing heat sink it is not possible simply to change from air to water.

A simpler, yet still highly effective, design passes the water in a copper tube through an aluminum plate to which the heat rejecting device is mounted. This style of liquid-cooled heat sink is shown in Figure 3-4.

![Figure 3-4. Liquid-Cooled Heat Sink](image)

Figure 3-4 shows a double pass counter flow heat sink. A more effective system would be a double pass parallel flow heat sink. In the counter flow design, one side of the heat sink is at a higher temperature than the other due to the water picking up heat during the initial pass and then returning through the heat sink for the second pass. By using a parallel flow design, a uniform heat transfer is possible.
As a possible replacement for the forced air convection heat sink, parallel flow heat sink similar to that shown in Figure 3-4 was evaluated with an internal diameter of ¼\".

The heat sink dimensions are 7" long by 2" wide by 3/8" thick.

Table 3-9. Flow Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic Viscosity, Water</td>
<td>( \mu_w )</td>
<td>9.59E-04 N-s/m²</td>
</tr>
<tr>
<td>Thermal Conductivity, Water</td>
<td>( k_w )</td>
<td>0.606 W/mK</td>
</tr>
<tr>
<td>Density of Water</td>
<td>( \rho_w )</td>
<td>998 kg/m³</td>
</tr>
<tr>
<td>Specific Heat, Water</td>
<td>( C_{pw} )</td>
<td>4217 J/kg-K</td>
</tr>
<tr>
<td>Prandtl Number</td>
<td>( Pr )</td>
<td>6.62</td>
</tr>
<tr>
<td>Pipe Roughness</td>
<td>( \varepsilon )</td>
<td>1.50E-06 m</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>( T_c )</td>
<td>293 K</td>
</tr>
<tr>
<td>TEC HOT Side Temperature</td>
<td>( T_{tec,h} )</td>
<td>303 K</td>
</tr>
</tbody>
</table>

Table 3-10. System Dimensions.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Outside Diameter</td>
<td>( D_o )</td>
<td>0.009525 m</td>
</tr>
<tr>
<td>Tube Inside Diameter</td>
<td>( D_i )</td>
<td>0.00635 m</td>
</tr>
<tr>
<td>Tube Length (each)</td>
<td>( l )</td>
<td>0.1778 m</td>
</tr>
<tr>
<td>Tube Thermal Conductivity</td>
<td>( K_{tube} )</td>
<td>401 W/mK</td>
</tr>
<tr>
<td>Epoxy Thermal Conductivity</td>
<td>( K_{epoxy} )</td>
<td>0.72 W/mK</td>
</tr>
</tbody>
</table>

The maximum heat transfer was calculated for different fluid velocities. It was necessary to calculate the flow conditions for each fluid velocity. Equations for the performance evaluation of the liquid cooled heat sink are presented for a flow velocity of 0.4 m/s.

First, the Reynolds number was calculated. It was found that for flow rates below 0.15 gallons per minute (GPM), fluid flow through the tube is laminar. At flow rates above 0.15GPM, the flow becomes turbulent. The fluid flow is considered turbulent when the Reynolds number is over 2,300.
Before the convection coefficient could be determined, the Nusselt number was approximated, by (3-32).

\[ Nu = 3.66 (Re < 2300) \]
\[ Nu = 0.023 \cdot Re^{\frac{2}{3}} \cdot Pr^{0.3} (Re \geq 2300) \]  
\[ Nu = 0.023 \cdot 2643^{\frac{2}{3}} \cdot 6.62^{0.3} \]
\[ Nu = 22.2 \]

After determining the Nusselt number, the convection coefficient for the fluid flow was calculated.

\[ h = \frac{k_w \cdot Nu}{D_i} \]
\[ h = \frac{0.606 \frac{W}{m \cdot K} \cdot 22.2}{0.00635 m} \]
\[ h = 2115.4 \frac{W}{m^2 \cdot K} \]

For laminar flow, the convection coefficient was constant at 349.3 Wm²K. At the start of turbulent flow, the convection coefficient was much greater than that of the laminar region.
The overall heat transfer coefficient was calculated for the fluid flow using (3-34). The overall heat transfer coefficient accounts for the effects of the thermal conductivity of the tube.

\[
HT_{oal} = \frac{1}{h} \cdot \frac{D_t}{K_{tube}} \cdot \ln \left( \frac{D_o}{D_t} \right)
\]

\[
HT_{oal} = \frac{1}{2115.4 \frac{W}{m^2 K}} \cdot \frac{0.00635m}{401 \frac{W}{mK}} \cdot \ln \left( \frac{0.00953m}{0.00635m} \right)
\]

\[
HT_{oal} = 2087.1 \frac{W}{m^2 K}
\] (3-34).

To account for the convection transfer through the tube, the convection coefficient was reduced by approximately 2%. It was then necessary to determine the log mean temperature difference for flow through the tube. Before the log mean temperature difference was calculated, it was necessary to determine the output temperature of the heat sink. The exit temperature was determined using (3-35).

\[
T_o = T_h - \left( T_h - T_i \right) \cdot e^{-\frac{HT_{oal} \cdot \pi \cdot D_t \cdot l}{m \cdot C_v}}
\]

\[
T_o = 303K - \left( 303K - 293K \right) \cdot e^{-\frac{2087.1 \frac{W}{m^2 K} \cdot \pi \cdot 0.00635m \cdot 0.1778m}{0.01264 \frac{W}{m^2 K} \cdot 4217 \frac{W}{KgK} \cdot 0.00635m \cdot 0.1778m}}
\]

\[
T_o = 294.3K
\] (3-35).

The log mean temperature difference was calculated through (3-36).
Once the log mean temperature difference for the flow through the tube was calculated, it was possible to calculate the assembly's maximum heat transfer. This was calculated using (3-37).

\[
\Delta T_{lm} = \frac{(T_h - T_o) - (T_h - T_i)}{\ln\left(\frac{T_h - T_o}{T_h - T_i}\right)}
\]

\[
\Delta T_{lm} = \frac{(303K - 294.3K) - (303K - 293K)}{\ln\left(\frac{303K - 294.3K}{303K - 293K}\right)}
\]

\[
\Delta T_{lm} = 9.34K
\]

Once the log mean temperature difference for the flow through the tube was calculated, it was possible to calculate the assembly’s maximum heat transfer. This was calculated using (3-37).

\[
Q = HT_{out} \cdot \pi \cdot D_i \cdot 2 \cdot L \cdot \Delta T_{lm}
\]

\[
Q = 2087.1 \frac{W}{mK} \cdot \pi \cdot 0.00635m \cdot 2 \cdot 0.1778m \cdot 9.34K
\]

\[
Q = 138.2W
\]

It was found that with laminar flow, the liquid-cooled heat sink is capable of a maximum heat transfer of 24.3W. This is comparable with the similar sized convection-cooled heat sink. When the flow becomes turbulent, the maximum heat transfer increases significantly.
Figure 3-5 shows the maximum heat transfer through the heat sink as a function of the flow rate.

![2 Pass Parallel Flow 1/4" Liquid System](image)

Figure 3-5. Maximum Heat Transfer Through Heat Sink, by Flow Rate.

**Table 3-11. System Calculations**

<table>
<thead>
<tr>
<th>U</th>
<th>Re</th>
<th>Nu</th>
<th>DP</th>
<th>h</th>
<th>HToa</th>
<th>Toot1</th>
<th>DTlm</th>
<th>q</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>GPM</td>
</tr>
<tr>
<td>0.1</td>
<td>660.8</td>
<td>3.7</td>
<td>16.9</td>
<td>349.3</td>
<td>348.50</td>
<td>293.89</td>
<td>9.55</td>
<td>23.61</td>
<td>0.05</td>
</tr>
<tr>
<td>0.2</td>
<td>1322</td>
<td>3.7</td>
<td>33.9</td>
<td>349.3</td>
<td>348.50</td>
<td>293.45</td>
<td>9.77</td>
<td>24.16</td>
<td>0.10</td>
</tr>
<tr>
<td>0.3</td>
<td>1982</td>
<td>3.7</td>
<td>50.8</td>
<td>349.3</td>
<td>348.50</td>
<td>293.30</td>
<td>9.85</td>
<td>24.34</td>
<td>0.15</td>
</tr>
<tr>
<td>0.4</td>
<td>2643</td>
<td>22.2</td>
<td>130.4</td>
<td>2115.4</td>
<td>2087.09</td>
<td>294.30</td>
<td>9.34</td>
<td>138.24</td>
<td>0.20</td>
</tr>
<tr>
<td>0.5</td>
<td>3304</td>
<td>26.5</td>
<td>189.5</td>
<td>2528.9</td>
<td>2488.48</td>
<td>294.24</td>
<td>9.37</td>
<td>165.34</td>
<td>0.25</td>
</tr>
<tr>
<td>0.75</td>
<td>4956</td>
<td>36.7</td>
<td>376.0</td>
<td>3497.9</td>
<td>3421.02</td>
<td>294.14</td>
<td>9.42</td>
<td>228.53</td>
<td>0.38</td>
</tr>
<tr>
<td>1</td>
<td>6608</td>
<td>46.1</td>
<td>614.7</td>
<td>4403.0</td>
<td>4281.99</td>
<td>294.08</td>
<td>9.45</td>
<td>287.09</td>
<td>0.50</td>
</tr>
<tr>
<td>1.1</td>
<td>7269</td>
<td>49.8</td>
<td>724.1</td>
<td>4751.9</td>
<td>4611.20</td>
<td>294.06</td>
<td>9.46</td>
<td>309.53</td>
<td>0.55</td>
</tr>
<tr>
<td>1.2</td>
<td>7930</td>
<td>53.4</td>
<td>841.1</td>
<td>5094.5</td>
<td>4933.09</td>
<td>294.04</td>
<td>9.47</td>
<td>331.49</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Based on heat transfer capabilities, it seems that using a liquid cooled heat sink would be ideal. However, the heat which has been transferred from the base mold into the water must still be dissipated to the air. The most common method is the use of a radiator.
During machine operation, all eight base mold assemblies will be active at a time. Each assembly will have one active base mold at a time. Operating at a set voltage of 5.8V, the thermal electric cooler ideally is capable of transferring a maximum of 17.5W. With eight assemblies operating, 140W of neat must be dissipated by the radiator. The size of the required radiator is dependant on the convection rate of the air. The required radiator surface area was calculated through (3-38). Table 3-12 shows the required surface area of the radiator.

\[
A_s = \frac{140W}{h_a \cdot (T_o - T_h)}
\]  

(3-38).

Table 3-12. Radiator Surface Area

<table>
<thead>
<tr>
<th>H (air) W/m²K</th>
<th>Area m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>31.61</td>
</tr>
<tr>
<td>10</td>
<td>30.9</td>
</tr>
<tr>
<td>15</td>
<td>30.66</td>
</tr>
<tr>
<td>20</td>
<td>5.4</td>
</tr>
<tr>
<td>25</td>
<td>4.51</td>
</tr>
<tr>
<td>30</td>
<td>4.08</td>
</tr>
<tr>
<td>35</td>
<td>3.71</td>
</tr>
<tr>
<td>40</td>
<td>3.32</td>
</tr>
</tbody>
</table>

From Table 3-12, it can be seen that a large radiator will be required, which is not practical for implementation in the already-crammed AutoTEC machine. Apart from the radiator, additional circulation pumps and plumbing would be required. Great care must also be used to ensure that there are no coolant leaks onto the electrical systems contained in the lower portion of the machine. Because of the additional requirements needed for the implementation of a liquid-cooled system it was decided that it was not practical for use with the current machine.
4. Finite Element Analysis

4.1. Tools

Finite Element Analysis of the heat sink was performed using Ansys ProFEA software. The Ansys software is linked to Pro Engineer, which is the solid modeling software used in the development of the AutoTEC system.

The analysis was begun using Ansys version 6.1. Due to problems with the Windows operating system, it was necessary to upgrade to Ansys version 7.0. All the analysis which was performed using the version 6.1 software was re-evaluated using the new version 7.0. The newer version proved to be more stable and less prone to lockup than the version 6.1.

The first analysis was based on the existing Pro-Engineer model of the heat sink. This model was constructed during the development of the AutoTEC system. In order to reduce the complexity of the mesh, the features such as tapped holes and locating pins were removed. The model was initially drawn using the English unit system, but was converted to metric units for the computer analysis. The Newton-meter-second-Kelvin unit system was used.

4.2. Model Parameters

The existing model was very difficult to mesh. The solid model was complicated by the air passageways, which were modeled as patterned cutouts. This additional
geometry caused problems during the mesh generation phase. A new solid model was constructed with the air passageways modeled as standard cutouts.

The first step in the Ansys evaluation was the application of the heat loads and boundary conditions. This was done through Pro-Mechanica, a finite element plug-in for Pro-Engineer. The forced convection and fluid temperature were applied as a boundary condition to the inside of the heat sink. The convection coefficient was applied as 40W/m²-K. This value is based on the calculated convection coefficient during the theoretical evaluation of the heat sink. The air temperature was defined as being constant at 22°C (295 K). The direction of air flow could not be specified since Ansys did not have the option for applying directional convection flow.

The heat source was defined by making a shallow cut in the surface of the heat sink model. The cut was made at a depth of 0.005”. The surface of the cutout was defined as the heat load. A constant value of 13 W was defined for this surface at a constant temperature of 30°C (305 K).

Due to its large size, it was not possible to mesh the full size heat sink model using the available computer. Additional memory was added, increasing the system memory from 512 Megabytes to 1 Gigabyte. The additional memory did not help in the analysis of the full size model, and it was not possible to mesh the full size heat sink model.

4.3. Reduced Heat Sink Model Analysis

To reduce the problems encountered with the analysis performed in Section 4.1, it was decided to perform a second analysis using a smaller portion of the heat sink. During operation of the AutoTEC system, the large tissue base mold is used more
frequently than the biopsy base mold. The large tissue base mold is mounted nearest to the end of the heat sink where the air exits the internal passageways.

The reduced heat sink model (Figure 4-1) was sized at two and a half inches long. This dimension is based on the TEC mounting cutout which is one and a half inch square plus a half inch on each side of the cutout. The half inch spacing on each side was decided upon to provide symmetry, since the TEC cutout is located half an inch from the edge of the heat sink. This reduced size model was used in the hot side thermal modeling performed in Section 3.2.

![Figure 4-1. Heat Sink Model.](image)

The smaller model size reduced the amount of memory required for the analysis, and decreased the number of computer lockups.

As with the full size heat sink model, boundary conditions and heat loads were applied based on the system modeling performed in Chapter 3. The convection coefficient was defined as 40.0 W/m-K at an ambient temperature of 22°C (295 K).
The heat load was defined as 13 Watts at a constant temperature of 30°C (303 K) applied to the TEC mounting surface.

The mesh was created using the default size of 0.0032 m. After creation, a four pass mesh improvement was performed to fix errors within the mesh. Once created, the mesh was imported into Ansys for the thermal evaluation shown in Figure 4-2.

From Figure 4-2, it can be seen that the heat is concentrated near the upper surface of the heat sink. The TEC mounting surface is maintained at a constant temperature of 303 K during the cooling cycle. The surrounding areas of the upper surface ranged between 299–300 K in temperature, demonstrating the high thermal resistance of the fin array.

A small amount of heat does reach the lower surface of the heat sink judging by the minimum temperature displayed in the legend of 295.64 K. Since heat does reach the
lower surface, the assumption made during the system modeling in section 3.2 is questionable. The assumption made for the simplification of the heat sink modeling was that a negligible amount of heat reaches the lower surface. Since it was assumed that heat transfer does not occur at the lower surface, this factor was ignored in the heat transfer calculations. The 0.5 K temperature increase at the lower surface corresponds to 6% of the overall temperature difference of 8 K.

The thermal flux through the heat sink is displayed in Figure 4-3.

![Figure 4-3. Thermal Flux.](image)

The heat flux displays the rate of change in the heat flow. Figure 4-3 displays that the majority of heat transfer is occurring at the root of the fins. The heat transfer occurs nearest to the upper surface since flow through the heat sink is restricted by the high thermal resistance.
4.4. Modified Heat Sink Analysis

The heat sink design analyzed in Section 4.3 was modified in an attempt to improve its heat transfer abilities. The thickness of the upper surface was increased to 0.1875 inches while the length of the internal fins was increased to 2.125 inches. The modified heat sink design is shown in Figure 4-4.

![Modified Heat Sink Design](image)

Figure 4-4. Modified Heat Sink Design.

The same boundary conditions and heat loads defined for the Section 4.3 analysis were applied. The same values for the mesh creation and improvement were also used. The plot of temperature distribution is shown in Figure 4-5.
Figure 4-5. Modified Heat Sink Temperature Distribution.

The effects of the increased surface thickness can be seen in comparing Figure 4-2 and Figure 4-5. The areas surrounding the TEC mounting surface are more uniform in temperature distribution due to the extra material. The root of the fin array is at a uniform temperature of 299 K.

The increase in fin length resulted in less heat reaching the lower surfaces of the fins. The temperature at the end of the fins did not increase significantly compared to the ambient temperature of the airflow.

Comparing the original heat sink to the modified heat sink, it can be seen that by increasing the fin length and the upper surface thickness, the amount of heat which could be dissipated was increased.
4.5. **Production Heat Sink Analysis**

A second heat sink was designed improving upon the original heat sink as well as the modified heat sink evaluated in section 4.4. The new heat sink was modeled for easier and more cost effective manufacture.

The new heat sink was designed for use in the beta prototype machine. The heat sink used in the beta machine is larger than in the previous machine. The thickness of the upper surface was further increased to 0.23". To accommodate more fins, the width of the heat sink was increased to 3". The resulting design has fourteen 3" fins, with a spacing of 0.13" at the base. A ½° draft was applied to the fins to improve the heat transfer capabilities.

The fin array (Figure 4-6) was not enclosed as in the original heat sink. The tooling required for extruding the heat sink is much simpler for the open fin array compared to the enclosed array. A cover plate is to be used for closing off the fin array.

Figure 4-6. New Heat Sink Model.
To compare the new heat sink design to the earlier one, the same convection coefficient and heat load were applied to the new design.

The heat sink model (Figure 4-7) was constructed with a draft feature for the creation of the fin taper, but due to problems with the mesh creation it was changed to a cutout. The mesh was created with a default size of 0.004 m. A four pass cleanup was performed to improve the mesh.

Figure 4-7. Temperature Distribution in New Heat Sink.

The increase in surface thickness helped to distribute the heat more evenly through the heat sink. With the exception of the areas nearest to the TEC mounting surface, the upper surface is uniform at 300.5 K. This includes the outer fins of the heat sink, since the outer surfaces are not exposed to convection.

Due to the increase in fin length and change in fin geometry, less heat reached the tips of the fins, as indicated by the minimum temperature of 295.218 K displayed in
the legend. This minimum temperature corresponds to an increase over ambient of approximately 0.07 K. Since the heat sink does not have an enclosed lower surface, it will be necessary to incorporate a cover into the design of the assembly so that the airflow is channeled through the heat sink.

The thermal flux through the heat sink is shown in Figure 4-8.

![Figure 4-8. Thermal Flux in Final Design](image)

As with the original heat sink design, the highest thermal flux occurs around the TEC mounting surface. The roots of the fins in the array also display high thermal flux due to the heat transfer to the ambient air.

### 4.6. Second Analysis of New Heat Sink

As a result of the change in heat sink size, the convection coefficient calculated for the original heat sink design does not apply to the new heat sink design. The calculation of the convection coefficient for the new heat sink is shown in Chapter 3.
The convection coefficient calculated for the new heat sink was 45.43 W/m²K. The airflow through the new heat sink is turbulent, due to the geometry of the heat sink, and the 7 m/s air velocity is slightly increased due to new fans used in the design. The convection coefficient used in the analysis was 45 W/m²-K.

The second analysis of the new heat sink design was performed for the proposed supply voltage increase to 7.0 VDC. The heat load applied to the TEC mounting surface was set at 17 W to reflect the heat transfer from the TEC. The interface temperature of 303 K did not change as a result of the voltage increase (Figure 4-9).

Figure 4-9. Heat Sink Temperature Distribution.

The results from the second analysis are virtually identical to those from the first. Due to the higher convection coefficient, less heat reaches the fin tips. The heat distribution through the heat sink is similar, with the outer fins at a higher temperature due to the absence of convection on the exterior surfaces.
The heat sink shown in Figure 4-6 was approved for production based on the preliminary results of the analysis and the system modeling. The main factor in the acceptance of the heat sink was the rushed time line for the machine assembly. The assembly of the beta unit required a decision of which heat sink design to use. Since the new heat sink was capable of more thermal dissipation, it was chosen for use in the beta unit.
5. Experimental Analysis

Several experiments were performed in order to evaluate the performance of the initial base mold assembly as well as the experimental assemblies. The test procedures are detailed in the Appendix. The tests were developed specifically for the testing of the base mold assembly. The construction of the test assemblies as well as the testing of the assemblies is detailed in this section.

5.1. Construction of Soldered Assemblies 1 and 2

The construction of a working soldered assembly was to be performed once the required materials were obtained. Initially, it was hoped that it would be possible to order the high temperature TEC module (HT8-12-40) with a solderable metalized finish. Discussion with Melcor technicians indicated that the high temperature modules could not be metalized due to problems with failure as a consequence of thermal expansion.

The special ceramic material of which the surfaces of the thermoelectric coolers are made cannot withstand thermal expansion when mounted in a soldered junction. When mounted using thermal interface pads and compressive force, the module can expand and contract along two axes as it is cycled. When soldered, the TEC does not have this freedom to expand and contract.
It was therefore necessary to order a different thermoelectric cooler which was capable of being soldered. Melcor manufactures a solderable module similar in size and heat transfer capacity to the model HT. The part number for the solderable TEC selected is CP1.4-127-045 m/m. This TEC has the same physical size as the model HT. The model CP has a maximum continual operational temperature of 80°C, whereas the model HT has a maximum continual operational temperature of 212°C. Figure 5-1 shows a side-by-side comparison of the CP1.4-127-045 m/m and HT8-12-40 (white) models.

![Figure 5-1. TEC Module Comparison](image)

Exposure to temperatures over 80°C for prolonged periods of time causes the internal solder within the model CP TEC module to degrade and lose heat-pumping capacity. Exposure to elevated temperatures for short periods of time is permissible. The internal solder – a bismuth-tin alloy – melts at a temperature of 138°C. Melcor does not recommend exposure to temperatures above 110°C, however.

During operation, the base mold is heated to a maximum temperature of 65°C. This temperature is maintained by a closed-loop feedback control. Since the
maximum temperature will not approach the operational limit of the TEC module, this lower operating range was not seen as a major drawback.

Two solderable model CP thermoelectric coolers were ordered from Melcor. In addition, special low temperature solder was ordered for the construction of the soldered assembly. Melcor offered two types of low temperature solder, both composed of a blend of Indium, Cadmium, and Tin. The two solder types differ in their component mixture percentages, which give two different melting temperatures. One solder type melts at 117°C, while the other melts at a temperature of 93°C. For the construction of the soldered assembly, it was decided to use the lower temperature solder to reduce the chances of damage to the TEC. The solder is available in pellet form, unlike most electronic device solder which is only available in spool form.

Since both the base mold and heat sink are made of aluminum, it was necessary to have the surfaces which were to be soldered copper plated. Initially it was intended to only have the TEC mounting surfaces copper plated, but the components were fully plated as a free sample by Burton Metal Finishing.

Since the plated heat sink and base mold were previously clear anodized, it was necessary first to strip the anodized finish from the aluminum. The parts were then cleaned with acid to remove chemicals from their surfaces. The base mold and heat sink were then zinc plated. The zinc plating acts as a substrate for the copper plating since it is not possible to directly apply the copper to the aluminum. Once the copper plating was applied, the surfaces were ready for soldering.
Prior to soldering, Melcor customer support was contacted to discuss the proper soldering method. Posted on the Melcor web page is a basic procedure for soldering the TEC. The procedure was revised to accommodate the materials and supplies which were available.

The heat sink and base mold required tinning in order for the soldering process to be performed. The mounting surfaces were cleaned by lightly abrading the surfaces with Scotch-Brite and denatured alcohol pads. An electric hot plate was used to heat the base mold and heat sink. The temperature of the components was measured using a hand-held thermocouple reader. The heat sink and base mold were heated to approximately 110-120°C.

A flux pen was used to apply flux to the surfaces for the soldering. The type of flux contained in the pen did not work very well with the type of solder used. The temperature of the soldering iron was set to the minimum temperature of 450°C. It was not necessary to reduce the supply current further since the components do not have a limiting temperature as the TEC does. The solder was evenly spread across the mounting surfaces using the soldering iron. After soldering, the heat sink and base mold were left on the hot plate. The hot plate was adjusted to maintain the temperature of the mounting surfaces at approximately 110°C.

The surfaces of the TEC were cleaned using denatured alcohol, and lightly abraded using fine Scotch-Brite. The surface was fluxed using the flux pen. The soldering iron was connected to the variable transformer, and adjusted until the tip temperature stayed below 110°C as read by the hand-held thermocouple reader.
As with the base mold and heat sink, the tinning process was difficult using the flux pen. It was found that the tinning process was much easier if the TEC was turned on and switched so that the side being tinned was heated. Both surfaces of the TEC were tinned in the same manner.

Once the TEC was tinned, the temperature of the heat sink surface was measured as 105°C. The TEC was turned on, and the heated side was placed onto the heat sink first. The TEC was held down with compressive force until the excess solder flowed out of the junction. The cooling fans were then connected to power and used to remove the heat from the heat sink.

Once the heat sink and TEC were cooled sufficiently, the supply current was switched, and the upper surface of the TEC was heated. Once the TEC was warm, the already heated base mold was placed on the TEC and held down with compressive force until the excess solder flowed out of the system. The TEC current was switched so that heat was rejected from the base mold to the heat sink, and the fans were turned on to blow air on the base mold. The soldered assembly can be seen in Figure 5-2.

Figure 5-2. Close-Up View of Soldered Base Mold Assembly
The first soldered assembly was found to be faulty after two performance tests were carried out. The fault lay in the preparation of the TEC surfaces. During the cleaning process, the surfaces had been lightly abraded using Scotch-Brite. This damaged the thin gold flash on the base plating of nickel on the surfaces of the metalized TEC. The abrasion damaged the gold flash, so that solder could not adhere to the metalized surface.

The assembly was disassembled and the components were cleaned. The heat sink and base mold were cleaned with denatured alcohol and Scotch-Brite abrasive pads. A new TEC was prepared for soldering. The surface of this TEC was not abraded, merely cleaned with denatured alcohol.

Melcor technical help was contacted to discuss improvements to the soldering procedure. It was found that the correct flux for the solder used is an organic-acid type. A container of suitable flux was found and used for the assembly. The second assembly was constructed in the same manner as the first, but using the organic-acid soldering flux.

The tinning process was much easier when the organic acid flux was used. The only downside was the odor of the evaporating flux. The plenums and fans were assembled to the heat sink, and calibrated thermocouples were glued to the base mold using Loctite #420 Adhesive.
5.2. Standard Base Mold Test

5.2.1. Objective

As a means of comparing the performance of the operational base mold system to that of the first soldered assembly, the base mold validation test detailed in the Appendix was performed on the two assemblies. To compare the performance of the two different mounting methods accurately, the TEC modules were tested using the compression mount method as a base line comparison. The data from the compression mounted test was then compared to the data recorded for the soldered base mold assembly using the same test procedure.

5.2.2. Experimental Procedure

The TEC modules tested in this experiment were manufactured by Melcor. The first module tested was the HT8-12-40. The second TEC module which was tested was the model CP1.4-127-045 m/m.

It was hoped that the model HT would be available in a solderable form, but due to problems with thermal expansion in that particular module, metallization is not offered. Instead, a different TEC module (CP1/4-127-045 m/m) was ordered. This TEC module has the same performance characteristics as the HT series, but with a lower operational temperature. The experimental setup is shown in Figure 5-3.
Since direct testing between the soldered model CP M and the compression mounted HT would have too many variables, it was necessary to perform a two step comparison. The performance of the model HT was compared to that of the metalized model CP while compression mounted. This was done as a means of determining if the TEC modules performances were equal as the manufacturer claimed, and to determine if the addition of the metallic film affects the performance. Once this comparison was complete, the performance of the soldered system could be accurately compared to that of the existing system.

This test was performed before the development of the standardized thermocouple construction and calibration procedures shown in the Appendix: Test Procedures, sections A.1 and A.2 respectively. The thermocouples used in this experiment were constructed in a similar manner to that discussed in section 1 of the Appendix, but were not welded together using the laser welder. Instead, the thermocouple junction was formed by standard electrical solder. For this experiment, the Hart Scientific dry well was used to calibrate the thermocouples at four different data points distributed over the experimental range.
Under the standards developed in the thermocouple calibration procedure, several of the thermocouples would not have been used due to significant temperature differences between the set point and sensed temperatures.

The thermocouples constructed in this experiment, and in later experiments were constructed from Omega type T thermocouple wire. The thermocouple wire has a stated accuracy being the greater of ±1°C or 0.75%. The calibration data for the specific thermocouples used in this experiment are shown in the Appendix.

The base mold assembly used in the testing of the compression mounted assembly was assembled according to the Base Mold Assembly procedure detailed in section 3 of the Appendix. The same heat sink and base mold were used for the compression mount testing of the TEC modules. The thermal interface pads were changed between the testing of each module.

The digital multi-meter used for voltage and current measurements in this and all other experiments was a Fluke model 77II. The instrument accuracy for voltage readings is ±0.3% + 1 digit. The instrument accuracy for current readings is ±1.5% + 2 digits.

5.2.3. Results

For this experiment, five data trials were recorded for each TEC module while compression mounted. Due to procedural errors and fluctuation in supply voltage, several data trials were rejected. Data was recorded for the ambient temperature, the heat sink entrance and exit, and the RTD mounting position on the base mold.
The recorded data was then normalized with respect to an ambient temperature of 22°C. This was necessary to reduce the variability of the data due to the fluctuation in ambient temperature. The measured RTD temperature value was adjusted by the ratio of the desired ambient temperature to the measured value.

The temperature recorded at the RTD position was normalized using Equations (5.1) and (5.2).

\[
F_c = \frac{22°C}{T_{amb} °C}
\]  
\[
T_{amb(norm)} = T_{amb} \cdot F_c
\]

After normalization, the validity of the recorded data was determined using Chauvenet’s Criterion. During the testing of both thermoelectric coolers, 326 data points were recorded for each trial. The mean and standard deviation were calculated for each of the 326 data points across the five data trials. After the determination of the mean and standard deviation, it was necessary to calculate the difference between the individual points versus the respective mean for the data point. The calculated difference was then divided by the standard deviation. For data sets of five trials, Holman [1994] states that the ratio of maximum acceptable deviation to standard deviation is 1.65.

Since the recorded data is part of a series, it was not possible to discard a single point because it was deemed bad. The percentage of points which did not meet the ratio of 1.65 was calculated for the five data trials. Trials with percentage of valid data below 90% were deemed bad. The third trial recorded for the model HT
was rejected due to only 38% of the data being below the ratio for data rejection. No data was rejected for the model CP M.

The AutoTEC system receives feedback information from an RTD mounted on the side of the base mold. Since this is the critical point used for machine operation, this location was used to track the base mold temperature during the experiment. The averaged RTD position temperature data for each TEC module is shown in Figure 5-4.

![Average Cooling Profile, (Normalized 22 deg C)](image)

Figure 5-4. Averaged RTD Position Temperature

Both modules were connected to a temperature controller to maintain the maximum temperature at a set point of 60°C. The model HT reached an average maximum temperature of approximately 57°C while the model CP m/m reached an average of approximately 55°C. Once thirty seconds had elapsed, the TEC modules were switched from heat to cool.

The cooling curves for the two modules displayed virtually identical behavior. During the transient phase of the cooling curve (30-80 seconds), the data are very
close. The same holds true for the steady-state portion (80-210). The average steady-state temperature reached during cooling for both modules was \(-2^\circ\text{C}\).

The data recorded for the individual trials was very consistent with that of the average. The recorded data did not have any significantly outlying trials. Since the actual data was very close in relation to the average, a true comparison between the two modules can be made using the average of the recorded data trials. The individual trial plots for the model HT are displayed in Figure 5-5, and those for model CP m/m in Figure 5-6.

![RTD. Position, 2.4g Paraffin. Model HT Std Mount](image)

Figure 5-5. Trial Plots for Model HT
The first trial was rejected due to the source voltage being greater than 5.80±0.1 VDC. The voltage was corrected for the remaining five data trials, and remained within the specified tolerance. The fourth trial was rejected because of outlying data.

Table 5-1 shows the averages of the recorded data.

Table 5-1. Model HT Trial Performance Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 5</th>
<th>Trial 6</th>
<th>Overall</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S. Hot Temp.</td>
<td>57.14</td>
<td>58.22</td>
<td>57.76</td>
<td>59.03</td>
<td>58.04</td>
<td></td>
</tr>
<tr>
<td>S.S. Cold Temp.</td>
<td>-2.26</td>
<td>-2.19</td>
<td>-3.05</td>
<td>-2.55</td>
<td>-2.51</td>
<td>°C</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>22.69</td>
<td>22.69</td>
<td>22.88</td>
<td>22.74</td>
<td>22.75</td>
<td>°C</td>
</tr>
<tr>
<td>Exit Temp.</td>
<td>23.79</td>
<td>23.71</td>
<td>24.09</td>
<td>23.80</td>
<td>23.85</td>
<td>°C</td>
</tr>
<tr>
<td>ΔT, Heat Sink</td>
<td>1.10</td>
<td>1.02</td>
<td>1.21</td>
<td>1.05</td>
<td>1.09</td>
<td>°C</td>
</tr>
<tr>
<td>Paraffin Weight</td>
<td>2.408</td>
<td>2.417</td>
<td>2.412</td>
<td>2.408</td>
<td>2.41</td>
<td>g</td>
</tr>
<tr>
<td>S.S. Current</td>
<td>2.86</td>
<td>2.91</td>
<td>2.89</td>
<td>2.91</td>
<td>2.89</td>
<td>A</td>
</tr>
<tr>
<td>S.S. Voltage</td>
<td>5.79</td>
<td>5.79</td>
<td>5.8</td>
<td>5.79</td>
<td>5.79</td>
<td>V</td>
</tr>
</tbody>
</table>
As with the data recorded during the testing of the model HT, the data trials of the model CP m/m (Figure 5-6) were tightly grouped. Trial 2 was rejected due to an error in the dispensing of the paraffin.

It can be seen that the ambient temperature did not fluctuate significantly, remaining near 22.7°C. The weight of the dispensed paraffin remained relatively constant at 2.41g throughout the data trials.

The averages for the trial data are shown in Table 5-2:

Table 5-2. Model CP m/m Trial Performance Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cycle 1</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Cycle 6</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S. Hot Temp.</td>
<td>56.15</td>
<td>53.80</td>
<td>51.93</td>
<td>54.92</td>
<td>55.00</td>
<td>54.36°C</td>
</tr>
<tr>
<td>S.S. Cold Temp.</td>
<td>-3.10</td>
<td>-2.19</td>
<td>-1.25</td>
<td>-3.29</td>
<td>-3.08</td>
<td>-2.58°C</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>22.57</td>
<td>22.82</td>
<td>24.05</td>
<td>23.04</td>
<td>22.48</td>
<td>22.99°C</td>
</tr>
<tr>
<td>Exit Temp.</td>
<td>24.34</td>
<td>24.28</td>
<td>25.61</td>
<td>24.57</td>
<td>23.67</td>
<td>24.49°C</td>
</tr>
<tr>
<td>ΔT, Heat Sink</td>
<td>1.77</td>
<td>1.45</td>
<td>1.56</td>
<td>1.54</td>
<td>1.19</td>
<td>1.50°C</td>
</tr>
<tr>
<td>Paraffin Weight</td>
<td>2.56</td>
<td>2.47</td>
<td>2.49</td>
<td>2.45</td>
<td>2.42</td>
<td>2.48g</td>
</tr>
<tr>
<td>S.S. Current</td>
<td>2.6</td>
<td>2.62</td>
<td>2.59</td>
<td>2.61</td>
<td>2.62</td>
<td>2.61A</td>
</tr>
<tr>
<td>S.S. Voltage</td>
<td>5.78</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.80V</td>
</tr>
</tbody>
</table>

The ambient temperature fluctuated more drastically in the testing of the model CP than in the testing of the model HP. During trial 3, the ambient temperature averaged 24°C. Due to the high ambient temperature during trial 3, the steady-state cold temperature was much higher than the other data trials.

Comparing the data in Table 5-1 with that in Table 5-2, the major difference is in the steady-state current. The average steady-state current for the model HT thermal electric cooler was 2.90 Amps. During the testing of the model CP, the steady-state current averaged 2.61 Amps. The two modules displayed nearly identical
performance, but the model CP was more efficient, requiring 0.31 Amps less than that of the model HT.

The results of the compression mounted assembly testing for the two thermal electric coolers shows that the two modules perform the same while under similar conditions. The only difference in performance found during the test was the lower current draw for the model CP.

5.3. Construction of Soldered Assembly #3

Prior to the testing in section 5.4, the second soldered base mold assembly was found to be faulty. The module was cooled too rapidly after assembly, causing thermal stress which, in turn, broke the module. The damaged assembly was disassembled and cleaned using alcohol and Scotch-Brite abrasive pads. The failed TEC was discarded.

It was found that the hot plate used for heating the assembly was not very controllable. Because the hot plate heated the components from only one surface, a temperature gradient was produced within the assembly. In particular, a great deal of heat was present in the lower areas. When the assembly was removed from heat and allowed to cool, the heat from the bottom of the assembly flowed upwards exposing the TEC to excessive amounts of heat for prolonged amounts of time.

In the place of the hot plate, a programmable convection oven was used. The controllability of the oven is far superior to that of the hot plate. The oven used was a Thermolyne model 30400CM. The temperature accuracy of this oven is ±2.5°C of the set point temperature.
Figure 5-7 shows the interior of the Thermolyne oven. Note the refractories used for spacing objects away from the heated surfaces, in order to prevent localized hot spots.

![Figure 5-7. Interior of Thermolyne Oven](image)

The pre-tinned heat sink and base mold were placed inside of the oven on the refractories. Two steel weights were also placed inside of the oven. These weights would later be used to apply compressive force to expel the excess solder from the assembly. The oven temperature was set to 100°C and allowed to reach steady state. During the heating process, the TEC was pre tinned in similar fashion as before, except the temperature of the soldering iron was more closely monitored in order to reduce the chance of damage to the TEC.

Once the TEC was tinned the oven was opened, and the TEC was carefully placed in the proper location on the heat sink. The base mold was then aligned on the TEC. The two steel weights were placed on top of the base mold in order to press the base mold downward expelling the excess solder. The door was closed, and the oven was allowed to return to steady state. Figure 5-8 shows the assembly inside of the oven.
A timer was started when the oven door was closed. The assembly was left in the oven for ten minutes. At the end of this period, the assembly was checked to see if the solder had begun to flow. After eleven minutes, the solder was expelled and the assembly was removed from the oven.

Under advice from Melcor technicians, the assembly was allowed to air cool. This was done to reduce the effects previously encountered with forced cooling of the assembly. The assembly was allowed to cool overnight.

5.4. **Results of Continuous Cycle Test**

5.4.1. **Objective**

In order to make a better approximation of actual machine operation, a new test procedure was developed. This test method simulates the machine operation by consecutively cycling the base mold assembly within the same operational parameters obtaining in the AutoTEC system. This experiment was performed in
order to compare the performance of the soldered base mold assembly to that of the standard compression mount assembly.

5.4.2. Experimental Procedure

In the new test method, a standard frame was placed in the base mold and heated for thirty seconds. During the last five seconds of heat time, approximately 5g of paraffin was dispensed into the base mold. The base mold was then cooled for 210 seconds. The full experimental procedure is detailed in section 5 of the Appendix.

Testing was performed using a standard base mold assembly with the model HT8-12-40 TEC, a standard base mold assembly using the non-metalized version of the solderable TEC (CP1.4-127-045L), and the third soldered base mold assembly whose construction is detailed in Section 5.3. For each assembly, five data cycles were performed and recorded. The performance of the two assemblies was then compared based on the recorded data. The thermocouples used in this experiment were calibrated according to the procedure detailed in section 2 of the Appendix. The construction of the thermocouples was not performed according to the procedure detailed in section 1 of the Appendix, however. At the time of the experiment, the procedure had yet to be developed. The experiment was performed without the temperature controller connected to the base mold. The temperature controller was added to the procedure after the completion of this experiment.

Testing was first performed on the standard assembly with the model HT TEC. After testing, a model CP L TEC replaced the HT. Finally, the soldered assembly was tested. Five virgin frames were numbered and weighed for each assembly testing.
The frames used were model number 0000110-02 revision AA, lot number 100188671. The input voltage was measured at the TEC leads prior to the start of the experiment and set at 5.80V DC. The voltage was checked prior to the start of the soldered assembly testing as well. A constant volume syringe was constructed in order to dispense approximately 5g of paraffin.

The thermostat controlling the room temperature was adjusted to maintain an ambient temperature of approximately 22°C. The experimental limits are ±2°C of the desired ambient temperature.

Temperature data were recorded for several critical locations of the base mold assembly. The base mold temperature was measured at the RTD mounting location. The RTD is mounted on the flat surface of the base mold just above the TEC. The entrance and exit temperatures of the heat sink were recorded as well.

Chauvenet’s Criterion was not used for this experiment since it was performed as one continuous series, not individual trials. Therefore, elimination of a single data cycle is not possible as with the testing performed in Section 5.2.

5.4.3. Experimental Results

During the testing of the standard assembly, the ambient temperature of the room remained within the experimental limits. The average ambient temperature for this part of the experiment was 22.8°C. Figure 5-9 shows the performance curve for the standard base mold assembly:
The performance of the standard assembly with the model HT thermal electric cooler remained constant throughout the five recorded cycles. The minimum temperature reached during the cooling cycles was approximately $2^\circ C$ for each cycle. The average maximum temperature reached during the heating phase of the cycles was $57.3^\circ C$. During the first cycle the maximum hot temperature was $61^\circ C$. This increased temperature is because the first cycle began at ambient temperature. During the second through the fifth cycles, the heating cycle began at near freezing.

It may be seen from Figure 5-9 that the ambient temperature during the experiment did not fluctuate greatly. The heat rejection from the base mold through the heat sink to the air is visible in this figure. It can be seen that the exit temperature of the heat sink increases at the start of the cooling cycle when the heat is being
rejected. The exit temperature reaches a steady-state value of approximately 25°C during the cooling phase of the thermal cycle. The exit temperature then drops during the heating phase of the cycle. Figure 5-10 shows the individual cycle performance of the standard base mold assembly.

![Individual Cycle Performance, Model HT](image)

**Figure 5-10. Model HT Individual Cycle Performance**

The curves representing the individual cycles were separated every four minutes. The first thirty seconds represents the heating portion, the last 3 minutes 30 seconds the cooling time. Since the placement and removal of the frames was manually performed, there is slight variation in the time at which the cooling segment began. To account for this, the time scale was adjusted so that maximum temperature is placed at time equals zero.
Figure 5-10 shows that the individual cycle data is very close together. The base mold cools very rapidly during the transient portion of the curve. After about fifteen seconds, the cooling begins to slow. The base mold then asymptotically approaches the steady-state temperature of 2°C.

During the testing of the standard base mold assembly with the model HT thermal electric cooler, the module drew an average current of 2.93 amps while cooling an average paraffin weight of 4.93g. The performance data for the testing of the standard assembly is shown in Table 5-3.

Table 5-3. Standard Base Mold Performance Data (HT)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S. Hot Temp.</td>
<td>58.91</td>
<td>56.99</td>
<td>57.08</td>
<td>56.10</td>
<td>57.20</td>
<td>57.25</td>
</tr>
<tr>
<td>S.S. Cold Temp.</td>
<td>1.70</td>
<td>1.58</td>
<td>1.92</td>
<td>2.05</td>
<td>1.40</td>
<td>1.73</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>22.92</td>
<td>22.74</td>
<td>22.70</td>
<td>22.63</td>
<td>22.88</td>
<td>22.77</td>
</tr>
<tr>
<td>Exit Temp.</td>
<td>24.65</td>
<td>25.05</td>
<td>25.07</td>
<td>25.12</td>
<td>25.29</td>
<td>25.04</td>
</tr>
<tr>
<td>ΔT, Heat Sink</td>
<td>1.72</td>
<td>2.31</td>
<td>2.38</td>
<td>2.49</td>
<td>2.41</td>
<td>2.26</td>
</tr>
<tr>
<td>Paraffin Weight</td>
<td>4.9962</td>
<td>4.7602</td>
<td>4.9583</td>
<td>5.0353</td>
<td>4.8267</td>
<td>4.92</td>
</tr>
<tr>
<td>S.S. Current</td>
<td>2.93</td>
<td>2.93</td>
<td>2.93</td>
<td>2.94</td>
<td>2.93</td>
<td>2.93</td>
</tr>
<tr>
<td>S.S. Voltage</td>
<td>5.81</td>
<td>5.81</td>
<td>5.81</td>
<td>5.81</td>
<td>5.81</td>
<td>5.81</td>
</tr>
</tbody>
</table>

The test results for the model CP1.4-127-045L TEC assembly were very similar to that of the model HT assembly. During the testing of the model CP L assembly, the ambient temperature averaged 23.46°C. During the start of the fourth cycle, the ambient temperature fluctuated. Briefly, the ambient temperature increased to 25°C. The minimum temperature reached during the cooling phase of the cycle averaged 1.5°C.
The shape of the cooling curve was identical to that of the model HT assembly.

The cooling curve for the model CP L is shown in Figure 5-11.
As with the model HT assembly, the first cycle reached the highest temperature. The minimum temperature reached during the cooling cycle decreased with each cycle. During the first cycle, the minimum temperature was approximately 2°C. By the fifth cycle, the minimum cold temperature was 1.2°C. This decrease in temperature corresponds to a slight decrease in the ambient temperature. During the first two cycles, the ambient temperature averaged 23.5°C while during the final three cycles; the ambient temperature averaged 23°C. The performance data for the model CP L base mold assembly is shown in Table 5-3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S. Hot Temp.</td>
<td>59.94</td>
<td>55.87</td>
<td>54.16</td>
<td>54.87</td>
<td>54.28</td>
<td>55.83</td>
</tr>
<tr>
<td>S.S. Cold Temp.</td>
<td>1.92</td>
<td>1.57</td>
<td>1.33</td>
<td>1.35</td>
<td>1.13</td>
<td>1.46</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>24.10</td>
<td>23.62</td>
<td>23.12</td>
<td>23.25</td>
<td>23.21</td>
<td>23.46</td>
</tr>
<tr>
<td>Exit Temp.</td>
<td>25.70</td>
<td>25.60</td>
<td>25.16</td>
<td>25.18</td>
<td>25.12</td>
<td>25.35</td>
</tr>
<tr>
<td>ΔT, Heat Sink</td>
<td>1.60</td>
<td>1.98</td>
<td>2.04</td>
<td>1.93</td>
<td>1.91</td>
<td>1.89</td>
</tr>
<tr>
<td>Paraffin Weight</td>
<td>4.93</td>
<td>5.01</td>
<td>4.95</td>
<td>5.00</td>
<td>4.92</td>
<td>4.97</td>
</tr>
<tr>
<td>S.S. Current</td>
<td>2.49</td>
<td>2.49</td>
<td>2.49</td>
<td>2.49</td>
<td>2.48</td>
<td>2.49</td>
</tr>
<tr>
<td>S.S. Voltage</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.80</td>
</tr>
</tbody>
</table>

Two things are of particular interest in a comparison of Table 5-3 and Table 5-3. First, the difference between the ambient temperature and the heat sink exit temperature is noticeably different between the two trials. The model HT had a greater temperature difference, averaging 2.26°C in comparison to 1.89°C as averaged by the model CP L. The second major difference between the two performances is the current draw of the modules. The model CP L pumped approximately the same amount of heat as the model HT, but at much lower
operating current. The steady-state current draw of the model CP L averaged 2.5 A while the model HT had an average steady-state current draw of 2.93 A.

The performance of the soldered assembly decreased during each successive trial. The module worked very well initially, reaching an average minimum temperature of -0.12°C for the first three cycles. During the fourth and fifth cycles, the minimum temperature averaged 1.3°C. This increase in the minimum temperature corresponds to a decrease in the current draw. The current draw steadily declined during each successive cycle from an initial draw of 2.15 A to a final value of 2.09 A.

The full cycle performance of the soldered assembly is shown in Figure 5-12.

Model CP M Soldered Temp. Profiles

Figure 5-12. Soldered TEC Results
The ambient temperature fluctuated significantly during the testing of the soldered assembly. The cycles with the lowest minimum temperatures corresponded to the lowest portion of the ambient temperature curve. Cycles four and five had the highest ambient temperature of approximately 24°C. Table 5-4 shows the average performance data for the soldered assembly.

Table 5-4. Soldered Assembly Average Performance Data

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
<th>Cycle 5</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.S. Hot Temp.</td>
<td>66.54</td>
<td>61.44</td>
<td>62.72</td>
<td>63.83</td>
<td>62.75</td>
<td>63.46°C</td>
</tr>
<tr>
<td>S.S. Cold Temp.</td>
<td>-0.09</td>
<td>-0.18</td>
<td>-0.09</td>
<td>1.13</td>
<td>1.52</td>
<td>0.46°C</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>23.61</td>
<td>22.52</td>
<td>22.30</td>
<td>23.61</td>
<td>23.72</td>
<td>23.15°C</td>
</tr>
<tr>
<td>Exit Temp.</td>
<td>25.14</td>
<td>24.25</td>
<td>23.95</td>
<td>25.19</td>
<td>25.63</td>
<td>24.83°C</td>
</tr>
<tr>
<td>ΔT, Heat Sink</td>
<td>1.53</td>
<td>1.74</td>
<td>1.65</td>
<td>1.59</td>
<td>1.91</td>
<td>1.68°C</td>
</tr>
<tr>
<td>Paraffin Weight</td>
<td>4.9648</td>
<td>4.9463</td>
<td>4.8615</td>
<td>4.9474</td>
<td>4.9048</td>
<td>4.92g</td>
</tr>
<tr>
<td>S.S. Current</td>
<td>2.15</td>
<td>2.13</td>
<td>2.1</td>
<td>2.11</td>
<td>2.09</td>
<td>2.12A</td>
</tr>
<tr>
<td>S.S. Voltage</td>
<td>5.81</td>
<td>5.82</td>
<td>5.83</td>
<td>5.83</td>
<td>5.84</td>
<td>5.83V</td>
</tr>
</tbody>
</table>

In order to make a better comparison of the results from the individual tests, their full cycle performances were plotted together. The transient curves for all three modules are identical. The performances of the model HT and model CP L are virtually identical, only differing on two cycles. Initially the soldered assembly reached a much lower steady-state temperature, but the steady-state temperature increased with each successive cycle. This can be seen in Figure 5-13.
5.4.4. **Experimental Discussion**

This experiment was performed in order to make a better comparison between the performance of a soldered base mold assembly and that of the original system consisting, with a compression-mounted model HT TEC. This evaluation was performed by subjecting the assemblies to continuous cycling, for a better simulation of actual machine operation.

Based on the results of this experiment, the change from the operational system to the soldered assembly did not show a significant difference in the performance of the base mold assembly. The cooling curves that were experimentally measured were very close in shape and value. The only significant difference in the operation of the two assemblies was that of the current draw. The soldered assembly required approximately 0.8A less current to transfer a similar amount of heat as the model HT.
The performance of the soldered assembly will be further evaluated in section 5.5. This continued experimentation was performed to determine whether the soldered assembly will be able to operate for an extended lifetime without degradation in performance.

5.5. Extended Testing of Soldered Assembly #3

5.5.1. Objective

In order to determine if the soldered TEC could handle the continuous cycling between heat and cold, it was planned to perform a prolonged test to approximate the expected life cycle of the TEC during machine operation. In previous cyclic testing, the performance of the soldered TEC showed a tendency to decay. For this reason it was decided that, before prolonged testing was performed, a shorter test should be performed to see if the TEC continued to deteriorate.

5.5.2. Experimental Procedure

Testing was performed using the third constructed soldered assembly. As with previous experiments, model 0000110-02 revision AA virgin frames from lot number 100188671 were used. A new rubber stopper was inserted into the constant volume syringe prior to the start of the experiment. This experiment was performed using the continuous cycle test procedure detailed in section 5 of the Appendix.

The TEC voltage was set at 5.80 V DC, and was measured using a Fluke model 77 II multi-meter. It was planned to continue testing as long as the TEC did not show signs of performance decay. At the time of the experiment, the data acquisition
software was limited to a maximum of 10000 cycles per data file. The file size limitation meant that a maximum of twenty five cycles could be recorded per data file.

Prior to the experiment, the thermocouples used were calibrated following the procedure detailed in section 2 of the Appendix. Thermocouples were used to record the temperatures of the heat sink entrance and exit, the RTD position on the base mold, and the ambient temperature of the room. The thermostat controlling the room temperature was adjusted to maintain the temperature at 22 ±2°C. The calibration data for the thermocouples used in this experiment is shown in the Appendix.

The data from the continuous base mold test was used as the starting point for the experiment. The assembly had not been used since the continuous cycle testing described in Section 5.4. Therefore, the current testing can be treated as a continuation of the previous test.

As with the previous experiment, a temperature controller was not used to control the heating portion of the cycle. The cooling fans were connected to the data acquisition power supply, at a constant voltage of 15.4V DC.

5.5.3. Experimental Results

Two data trials were recorded. The first trial consisted of nine useable cycles, while the second consisted of seven recorded cycles. Procedural error resulted in the premature termination of both data trials. In all, twenty-one cycles were recorded between the three sets of data trials. Figure 5-14 shows the combined data trials.
The ambient temperature fluctuated between 22 and 24°C. For the remaining cycles, the ambient temperature remained near 23°C. For this procedure, two thermocouples were used to record the ambient temperature at the location of the test. The ambient temperature was then taken as the average of the two thermocouple readings.

From the start of the recorded data, it is obvious that the performance of the TEC degraded with each continual cycle. The first two data cycle reached minimum cold temperatures of -0.37°C and -0.53°C respectively. The performance then began to decrease steadily with each successive cycle. By the start of the second data trial, the minimum temperature had increased to 1.47°C. The final temperature recorded during the third data trial was 3.65°C.
Through the first seven trials, the minimum cold temperature increased rapidly. Between trials seven and twelve, the temperature stabilized at approximately 1.8°C. After trial twelve, the temperature again increased rapidly, reaching a final value of near 4°C.

As the minimum cold side temperature increased, the steady-state current draw of the TEC module decreased. The supply voltage remained within the specified tolerance range of \( \pm 0.05V \) during three data trials. The expected current draw for the soldered module based on the ideal modeling detailed in Chapter 3.3 is 2.7A. The operating current measured during the first cycle was 2.15A. During the final cycle, the operating current had decreased to 1.8A. The minimum cold side temperature and steady-state current draw can be seen in Figure 5-15.

![Minimum Cold Temperature, Current Draw](image)

**Figure 5-15. Minimum Cold-Side Temperature and Steady-state Current Draw**
5.5.4. Experimental Discussion

Based on the results of this experiment, it was decided that the third soldered assembly was sufficiently damaged to be of no practical use. Testing with the assembly was halted since further experimentation would not give any useful data. The base mold assembly was placed back into the oven and disassembled.

This experiment demonstrated the delicacy of the construction process. Because the soldering temperature is so close to the critical temperature of the assembly, the process requires great care and precision. Because of the failure of the assembly constructed for this experiment, the soldering procedure was reviewed and improved.

5.6. Construction of Soldered Assembly #4

The failure of the third soldered assembly was determined to be from excessive temperature exposure during the pre-tinning of the TEC module. Had thermal expansion been the cause for the failure, the effects would have been more noticeable. Instead, either excessive temperature or too prolonged an application of the soldering iron caused the failure. The internal solder of the thermoelectric cooler begins to lose its heat pumping capability when exposed to temperatures over 80°C for long periods of time.

Tinning the TEC was a difficult procedure due to the limiting temperatures associated with the module. The melting temperature of the solder used in the assembly is 93°C. The internal solder used in the construction of the TEC module melts at 138°C. Spreading the solder on the surface required lengthy application of
the soldering iron tip. If the TEC module was not turned on during this process, the spreading was even more difficult.

To eliminate the need for tinning the TEC with the soldering iron, a new TEC module was ordered from Melcor. This module came pre-tinned with the 93°C eutectic solder used in the previous experiments. The TEC was pre-tinned using a dip tank. The dip tank operates by melting a puddle of solder in a shallow temperature-controlled bowl. The TEC is fluxed on the metalized surfaces and dipped into the molten solder. The solder adheres to the fluxed surfaces, forming a thin layer. This procedure is very quick, and does not run the risk of damaging the TEC through lengthy heating.

Figure 5-16 shows a pre-tinned model CP1.4-127-045 t/t TEC.

Figure 5-16. Pre-Tinned TEC

Once the new TEC arrived, it was cleaned using denatured alcohol. The surfaces of the heat sink and base mold were cleaned with denatured alcohol and lightly abraded using Scotch-Brite adhesive pads. The oven was turned on and set to
100°C. The heat sink and base mold were placed inside of the oven along with the two steel weights. The components were left in the oven for approximately three hours to ensure that they were at a uniform temperature.

The oven was opened, and the TEC was located on the heat sink. The base mold was then aligned using the locating pins pressed into the heat sink. The steel weights were placed on top of the base mold, and the assembly was placed back into the oven. The assembly was left in the oven for approximately ten minutes, until the solder began to flow out of the junctions. At this point, the assembly was removed from the oven and placed on a steel table. A common household fan was used to cool the assembly.

The final assembly is shown in Figure 5-17.

![Figure 5-17. Soldered Assembly #4](image)

The assembly was left to cool overnight. The excess solder beads were removed from the junctions, and the flux residue was cleaned using denatured alcohol. The
plenums and fans were re-installed and newly calibrated thermocouples were glued to the base mold.

5.7. **Extended Testing of Soldered Assembly #4**

5.7.1. **Objective**

This test was performed in order to evaluate the performance of a fourth soldered assembly, constructed using a pre-tinned thermoelectric cooler. Of particular interest was whether the new assembly would show signs of degradation as a result of thermal cycling.

5.7.2. **Experimental Procedure**

This experiment was performed using the continuous cycle test procedure detailed in the Appendix. New thermocouples were constructed and calibrated according to the procedures detailed in the Appendix. The soldering of the heat sink assembly was done following the TEC soldering procedure detailed in the Appendix.

5.7.3. **Experimental Results**

This experiment was performed in three parts. The first data trial consisted of eight cycles, the second of five, and the third of ten. During the first data trial, the ambient temperature was higher than the experimental tolerance of $22\pm2^\circ\text{C}$. Even though the experimental tolerance was exceeded, it was decided to continue recording of the data trial. In previous experiments, the TEC module failed rapidly; therefore any data recorded prior to failure is valuable. The average ambient temperature for the first data trial was $24.12^\circ\text{C}$. 
The thermostat setting was adjusted after the first data trial in order to lower the temperature closer to the experimental goal of 22°C. During the second data trial, the ambient temperature decreased steadily throughout the trial. The average ambient temperature during the second data trial was 23.4°C. This is still higher than the desired value, but within the acceptable range.

The third data trial was performed on a different date than the previous two experiments. The data acquisition software had been modified prior to the experiment. The new software is configurable for the pause in data recording. For this experiment, the pause was set at 0.5 seconds. This value turned out to be too large, resulting in fewer data points than the previous two experiments. Because of the long pause, the plots for the third trial are not as smooth as the other two. The ambient temperature averaged 21.7°C for the third data trial.

The data for the three trials was plotted consecutively to show how the TEC module performed during testing. This can be seen in Figure 5-18.
The effect of the ambient temperature can be clearly seen in comparing cycles 1-8 to cycles 14-24. Since the average ambient temperature was almost two degrees higher during cycles 1-8, it reached an average minimum temperature of 2.90°C, while during cycles 14-24 the minimum temperature averaged 0.2°C.

Due to the lower ambient temperature, the final trial reached a much lower maximum temperature during the heating portion. The first two data trials averaged 58.7°C, while the final data trial averaged 56.5°C. The mass of the paraffin volume for the first two data trials averaged 5.05 and 5.04g respectively. The average paraffin mass during the third data trial was 5.22g.
The voltage during the three data trails averaged 5.81 VDC. The average current draw during the first data trial was 2.68A. The average current draw for the second data cycle was very close to the first at 2.69A. The third trial averaged a current draw of 2.72A due to the lower ambient temperature. Unlike previous testing of soldered base mold assemblies, the current draw did not decrease as the testing progressed.

The average current draw for the combined experiment matches up well with the theoretical operating current for the TEC which was determined in Section 3.3. The theoretical operating point for the TEC based on a supply voltage of 5.80V and an ambient temperature of 22°C was calculated to be 2.72A.

5.7.4. Experimental Discussion

This test was performed in order to evaluate the performance of the soldered assembly constructed using a pre-tinned thermoelectric cooler. The objective of the test was to determine if the assembly can withstand prolonged thermal cycling.

During this test, the soldered assembly constructed with the pre-tinned TEC did not show any signs of degradation. As the test progressed, the ambient temperature decreased steadily, causing the minimum temperature do also decrease. The current draw of the module did not vary significantly during the testing of the assembly, staying at a value near 2.7A.

Based on the results of this experiment, it appears that using a pre-tinned TEC module eliminated the problem with failure during construction. The dip tinning method used by the manufacturer produces an evenly tinned TEC surface without
exposing the module to excessive temperature. The dip tinning method is described in section 5.6.

In this test, twenty-four data cycles were recorded. This is not enough data to conclusively determine whether the assembly will be able to withstand prolonged cycling however. In order to conclusively test the assembly, it is planned to construct additional assemblies and test them on the machine for 25,000 cycles without paraffin load. By automating the testing, it will be possible to reduce the time required for the experiment.

5.8. Operating Voltage Performance Test

5.8.1. Objective

This experiment was performed in order to determine changes in the performance using the new heat sink assembly resulting from an increase in supply voltage to the TEC module. This test was performed at the current voltage of 5.8V through 7.8V at 0.5V increments.

In addition to testing the performance of the TEC at increased voltage levels, the performance of the new heat sink can be compared to the old heat sink for the voltage trials recorded at 5.8V.

5.8.2. Procedure and Equipment

The test procedure used for this experiment was modified slightly from the standard continuous procedure detailed in Appendix. A temperature controller was added to this procedure to keep the hot side temperatures at a set point level of 62°C.
The temperature controller used was a Chromalox model 3204. The proportional band was set at 9.2. The derivative was turned off, and the integral was set to 0.1.

New thermocouples were constructed and calibrated according to the procedures detailed in sections 1 and 2 of the Appendix. T-type thermocouples were used to record temperature data.

New virgin frames were used for this experiment. The frames used were part number 0000110-02, lot number 100188671. Tissue Tek VIP embedding paraffin was used for this experiment.

The thermostat controlling the room temperature was set to cool, and the temperature adjusted to have an ambient temperature of approximately 22°C. This setting required only minor adjustment throughout the experiment. The doors to the room were closed, with the nearest door being locked.

5.8.3. Experimental Results

During the course of this test, the ambient temperature in the room which the experiment was performed remained within the specified temperature range of 22±2°C. During the experiment, the temperature remained within ±1°C. The accumulative average ambient temperature for the experiment was 21.97°C. The individual trial averages are shown in Table 5-5.
The ambient temperature steadily decreased throughout the experiment. Even though the average decreased, the temperature did not fluctuate significantly. The maximum ambient temperature during this experiment was 22.92°C, while the minimum was 21.08°C.

Table 5-5. Average Ambient Temperatures

<table>
<thead>
<tr>
<th>Voltage</th>
<th>$T_{amb}$ °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td>22.47</td>
</tr>
<tr>
<td>6.3</td>
<td>22.20</td>
</tr>
<tr>
<td>6.8</td>
<td>21.90</td>
</tr>
<tr>
<td>7.3</td>
<td>21.74</td>
</tr>
<tr>
<td>7.8</td>
<td>21.53</td>
</tr>
</tbody>
</table>
The cooling curves generated at the RTD position followed the same transient curve. The curves (Figure 5-19) begin to separate approximately 20 seconds after cooling began. The heating curve also follows the same profile throughout the experiment.

![RTD Position, Non Normalized](image)

Figure 5-19. RTD Position, Non-Normalized

The temperature controller kept the maximum temperature at approximately 62 ± 1°C. The 5.8V and 6.3V trials did not make it to 62°C before the 30 seconds of cooling time expired. This may be due to the controller attempting to avoid overshoot by slowing the response.

The average steady-state temperature reached for each voltage setting was determined based on the final 15 data points in each cooling cycle. As the voltage increased, the steady-state temperature decreased linearly at approximately 1-1.2°C
per 0.5V. The average steady-state temperature reached during the 5.8V trial was -1.4°C.

The data from the continuous trials was separated into four respective cycles for each voltage setting. These cycles were averaged and plotted so that when time equals zero, the cooling cycles begin. This plot is shown in Figure 5-20.

![Average RTD Position, Non-Normalized](image)

Figure 5-20. Average RTD Position, Non-Normalized

The effects of the added temperature controller can be noticed prior to the start of the cooling cycle. For the trials above 6.3V, the temperature controller held the maximum temperature at an average of 62°C. For the 5.8V trial, the temperature did not reach the desired value of 60°C. This may be due to the effect of the controller. When the temperature nears the set point, the controller will begin to reduce the
power supplied to the TEC as a means of reducing the overshoot. For the 5.8V trial, this reduction resulted in a lower temperature. If given more time, it would have made it to the set point.

A safety factor was introduced into the heating cycle by increasing the voltage supplied to the TEC. At 7.3V, the base mold reached 60°C 10.2 seconds before the end of the heating cycle. For 6.8V, it reached 60°C with 9.6 seconds to spare. This safety factor ensures that the frame and base mold will reach the maximum heated temperature uniformly.

The proposed TEC voltage to be used on the new board design is 7.0V. A voltage increase over this value would result in too large an increase in supply power, and additional heat buildup. Since data were not recorded at this value, the expected performance curve was interpolated based on the 6.8V and 7.3V data trials. The interpolation was performed for each data point using (5-1).

\[
T_{7.0} = \frac{(V_{7.0} - V_{6.8}) \cdot (T_{7.3} - T_{6.8})}{(V_{7.3} - V_{6.8})} + T_{6.8}
\]  

(5-1).

Figure 5-21 shows the interpolated profile compared to the 5.8V profile.
Based on the interpolated data, the average steady-state value to be expected at 7.0V under similar operating conditions was determined to be approximately -4.0°C. At 7.0V, the base mold should reach 0°C approximately 81.6 seconds after the cooling cycle begins. At 5.8V, the base mold reaches 0°C after 130.8 seconds of cooling time. This represents a 37.5% reduction in the time required to reach 0°C.
The average of the interpolated data points from the four cycles is shown in Figure 5-22.

Interpolated Goal Voltage, based on 6.8V & 7.3V Data

Figure 5-22. Average of Interpolated Points

Based on the recorded data for the 6.8 and 7.3V trials, the expected current draw at 7.0V was calculated to be 3.50A. The power supplied at the TEC leads would be 24.5W. For 8 base mold arrays, the maximum power requirement would be 196W.
It can be seen that the new heat sink dissipates heat at a faster rate than the old design. To compare the performance, the average RTD position temperature from the testing of the model HT recorded in Section 5.4 was plotted against the average RTD temperature recorded for the new heat sink. This can be seen in Figure 5-23.

![Heat Sink Comparison, Model HT (5.8V)](image)

Figure 5-23. Performance Comparison.

The transient cooling curve of the new heat sink is noticeable steeper than the curve for the old heat sink. This results in a faster transition to steady-state, and a lower steady-state temperature. The final temperature for the new heat sink was 1.5°C whereas the old design reached a final steady-state temperature of 1.5°C.
5.8.4. Experimental Discussion

Changing the supply voltage from 5.8V to 7.0V at the TEC will improve the system performance significantly. The base mold will heat up approximately 10 seconds faster, and cool approximately 50 seconds faster.

While increasing the supply voltage will improve the system performance, this change will require modification to the TEC controller boards as well as increased supply power. The power draw will increase from 130W to 196W for eight base molds operating simultaneously. This increase in supply power will require a higher draw from the wall outlet. More heat will be generated since larger power supplies will be required for the increased voltage.

In comparing the performance of the TEC mounted to the new heat sink to the performance measured in section 4.4, it can be seen that at the same voltage setting that the performance is better for the new heat sink. The steady state temperature recorded with the new heat sink was approximately 3°C less than that of the old heat sink for a similar ambient temperature of 22°C ±1°C.

5.9. Automated Testing of Soldered Assemblies

5.9.1. Experimental Objective

It was noticed during the development of the pre-production AutoTEC machines that the thermal interface pads used between the surfaces of the thermal electric cooler and the aluminum components were failing due to thermal fatigue. The repeated expansion and contraction of the interface pads caused them to crack and fail.
This experiment was performed to determine if the soldered base mold assembly constructed according to the method presented in 5.6 would be able to withstand repeated thermal cycling without premature failure.

Over the expected lifetime of the AutoTEC embedding center, each base mold assembly will be expected to embed over two million cassettes. Since testing for a full two million cycles would be extremely time consuming, a shorter test of 25,000 cycles is used. While this represents 1.25% of the total life expectancy, it will be performed in one continuous block. During normal operation, the machine will not embed 25,000 cassettes in one uninterrupted run.

5.9.2. Experimental Procedure

Five new thermoelectric coolers, model CP1.4-127-045 were purchased from Melcor. The modules were pre tinned with the 93°C eutectic solder used in the previous experiments. The modules were sealed with RTV silicone to prevent moisture or paraffin from entering the module.

Three additional heat sinks were copper plated. Initially, it was intended for only the TEC mounting surfaces to be copper plated, but after discussion with the plating vendor, it was decided that the additional cost was not warranted. Three standard large tissue base molds were copper plated. Only the lower surface of the base molds was plated. The remaining surfaces were already clear anodized. Two biopsy base molds were plated in a similar manner. The newly plated heat sinks are shown in Figure 5-24. Plated base molds are shown in Figure 5-25.
The TEC module soldered to the assembly tested in section 5.7 was damaged after the testing was concluded. The damaged TEC module was removed, and the assembly cleaned for re-construction.

The components were assembled following the procedure described in the Appendix. The assembly process was performed without difficulty. The surfaces were cleaned very well prior to the final assembly, and the TEC module was placed in the oven for a maximum of eight minutes. During previous assembly attempts, upwards of fifteen minutes had been required for the solder to flow from between the junctions.
Once the assemblies were soldered, the extra solder expelled from the junctions was carefully removed using a razor knife. The solder was saved for future use. The assemblies were then cleaned with denatured alcohol pads to remove any flux residue from the surfaces.

Following steps 14-16 of the base mold assembly procedure described in the Appendix, the thermal fuse and RTD were attached to the assembly. The fan spacers and fans were mounted to the assembly following steps 17-18. The completed assembly is shown in Figure 5-26.

Figure 5-26. Completed Assembly

The component wiring was then terminated for connection to the controller board of the prototype testing machine. This machine was intended to be an early prototype machine, but was not finished. Instead, it is used for testing of various system components. The controller board used in this experiment was the newly developed board with a source voltage of 7.0 VDC.
Four base mold assemblies were removed from the test machine and replaced with the completed soldered assemblies. The assemblies were screwed down to the machine, and the Delrin covers were mounted on top of the heat sinks.

The TEC controller board was connected to a test computer previously used for a similar experiment. The Visual Basic code used for the previous experiment was modified for this experiment. The code changes were made to only have the four soldered assemblies operational instead of all eight stations mounted to the machine.

**5.9.3. Experimental Results**

Early in the experiment – after the first cycle – one of the TEC modules failed. The failed assembly was the last to be constructed. It is possible that the module was defective, or that it had been exposed to excessive temperatures during the disassembly process. To speed up the time required for the disassembly, the process had been performed at 117°C. The heat sink and base mold were cleaned, and placed back into the oven. The temperature did not decrease very fast to the new set point of 98°C. The TEC was placed onto the assembly when the sensor in the oven recorded a temperature of 102°C, but the metal components might have been at an elevated temperature, which could have damaged the module.

The resistance of a new model CP 1.4-127-045 t93/t93 is approximately 2.6-2.9 Ohms. The resistance of the module after failure was 16.8 Ohms. At the time of failure, the maximum current which the module drew was 1.5 A compared to the normal value of 3.5 A. The module showed no physical signs of failure. Without the full disassembly of the module, it was not possible to determine whether the module
failed because of thermal expansion or because of the assembly process. The decline in the module's performance can be seen in Figure 5-27.

![Temperature Profile, Cycles 1-47. Base Mold 1](image)

Figure 5-27. Decline in Module Performance

It can be seen from looking at Figure 5-27 that the module's performance dropped off immediately. After the first cycle, the minimum temperature rapidly increased to a final value of approximately 20°C. After cycle 47, the module was disconnected and replaced with a non-soldered assembly that was then used for the recording of the ambient temperature.

Despite the early failure of the module, the test was continued using the other three assemblies. A standard interface pad mounted assembly was mounted in the place of the failed assembly, to measure the ambient temperature. The three remaining assemblies were cycled for an initial run of 613 cycles. The performance of a second module began to decrease approximately 250 cycles into the initial run. At this point, the minimum temperature had risen to an average of 1.6°C. At 420 cycles (25,200 seconds), the minimum temperature had risen to 3°C. The minimum cold
temperature of the second base mold reached a steady value of 20°C after 1,100 cycles (66,000 seconds). This is shown in Figure 5-28.

Figure 5-28. Temperature Profile, Base Mold 2

After 3,700 cycles, the second base mold assembly stopped cycling. The failure was not noticed immediately, as the test was being run automatically at the time of failure. During the next few days of testing, the TEC functioned intermittently for brief periods. The fuse was checked on the TEC controller board and was found to be functional. Cycling stopped suddenly because the soldered interface between the base mold and TEC separated. The base mold was still cycling, but because of the separation the RTD was not able to read the temperature changes.
The broken junction is shown in Figure 5-29.

![Figure 5-29. Broken Junction.](image)

The performance of the third base mold also declined early in the test. After 88 cycles, the minimum cold temperature began to increase. Between cycles 88 and 135 (5,280 and 8,100 seconds), the temperature remained near 4.8°C. After this point, the temperature again increased to 6.4°C.
Figure 5-30 shows the trend in the base mold performance.

![Temperature Profile, Cycles 83-250, Base Mold 3](image)

**Figure 5-30. Temperature Profile, Base Mold 3**

The third base mold assembly was the only operational assembly at the end of the experiment. Even though it was still functioning, its performance was noticeably reduced from the initial 1,000 cycles.

Of the four assemblies constructed for this experiment, assembly number four operated the longest without signs of deterioration. Initially, the minimum temperature reached during the cooling cycle averaged 0-1°C. The data for the fourth base mold required inspection due to electronic noise encountered with the computer interface. False values were removed from the recorded data series.

Through the first 4,000 cycles, the fourth assembly reached a minimum cold cycle temperature between 0-2.5°C. For the next 1,500 cycles, the minimum temperature increased to 6°C. The minimum temperature then began to decrease until it was below 3°C. This was unexpected since when the TEC begins to fail, it usually
degrades progressively. The reason for this decrease was determined to be the result of a decrease in ambient temperature during testing. The temperature drop corresponded to a decrease in ambient temperature from an average of 27°C to a value of 23°C. The decrease in ambient temperature occurred during the evening hours of that day of testing. During the evening hours, the lights were turned off, and no bodies were present within the room. The temperature drop corresponded to the cycles recorded between 326,000 seconds and 375,000 seconds. During the testing prior to the temperature increase, the ambient temperature was between 23-25°C.

The decrease in minimum cold cycle temperature was brief, however. The performance of the module rapidly began to decay, despite the fact that the ambient temperature did not change. This rapid decay in module performance can be seen in Figure 5-31.

![Temperature Profile, Base Mold #4](image)

Figure 5-31. Module Decay.
As with the second base mold assembly, the fourth assembly suddenly failed. The soldered junction between the base mold and TEC broke in similar fashion to the second assembly. The failure started after approximately 8800 cycles were completed. After inspection, the resistance of the TEC module was measured to be 25KΩ.

5.9.4. Experimental Discussion

This experiment was performed to determine if a soldered junction mounted base mold assembly would be able to withstand prolonged thermal cycling. Initial results had proved promising during previous testing, but this experiment conclusively demonstrated that the soldered junction would not be able to withstand the thermal cycling required of the base mold assembly. Of the four assemblies constructed for this experiment, only one was functioning at the end. Two of the assemblies failed completely, and stopped to cycling.

Apart from the first assembly, the base mold assemblies performed well at first to start with, reaching minimum cold cycle temperatures of 0-2.5°C. The performance of each assembly then began to degrade, albeit at different rates. After failure, the assemblies each had a significantly higher electrical resistance than a new module, an increase attributable to the failure of the internal thermocouple junctions.
6. Conclusions

6.1. Summary

The goals of this project were defined as follows:

- Develop a simple and repeatable method to solder base mold assemblies.
- Evaluate the performance of the soldered assemblies in comparison to the original design.
- Determine the increase in supplied voltage necessary to improve performance without drawing too much additional power.
- Evaluate the design of the existing heat sink to determine which modifications might improve performance.
- Simplify the manufacturing and assembly process for the base mold assemblies.

With the assistance of the manufacturer of the thermoelectric coolers used in the experiment, an assembly procedure was developed for the soldering of the TEC modules. The procedure was refined through experimental analysis and observations noted during assembly construction.

In the course of the experimental analysis, it was determined that the soldered junction could not withstand the required thermal cycling. During experimentation, module failures occurred because of improper assembly and thermal fatigue of the internal thermocouple junctions.
Prior to module failure, the soldered assemblies performed very well in comparison to the compression-mounted assemblies. At similar ambient temperatures, the soldered assemblies transferred heat more efficiently, drawing less current but removing heat at the same rate as the compression mounted assemblies.

The soldered modules could not withstand the thermal cycling required of the base mold assembly however. During testing, the performance of the soldered assemblies slowly deteriorated. The failure is due to decay in the internal thermocouple junctions.

Construction of the soldered assemblies often resulted in failures as well. If the module was exposed to temperatures above 80°C for extended periods of time, the internal solder deteriorated causing a reduction in heat transfer capabilities.

Through experimentation, it was found that changing the supply voltage from 5.8V to 7.0V improved the TEC module’s performance. Increasing the supply voltage allowed the base mold to heat up ten seconds faster during the heating cycle. During the cooling cycle, the voltage increase removed 33 seconds from the cycle time required to reach 0°C.

Through modeling and Finite Element Analysis (FEA) of the existing heat sink, improvements were identified and incorporated into a new design more suited for operational use. The main improvements observed were in heat sink geometry. In the original heat sink design, the upper surface was very thin (0.06"), resulting in high spreading resistance through the material. The one dimensional thermal resistance through the heat sink upper surface was calculated as being 0.005 W/m-K, while the spreading resistance through the upper surface was calculated as 0.0162 W/m-K.
It was hoped that increasing the thickness of the upper surface would decrease thermal resistance; however, this did not prove to be the case. The increase in the thickness of the upper surface resulted in a higher one dimensional thermal resistance. Percentage wise, the increase in thickness reduced the spreading resistance through the surface (0.032 K/W). In the original design, the spreading resistance was 300% higher than the one dimensional thermal resistance. In the production heat sink, the spreading resistance was calculated to be 0.023 K/W, or 75% of the one dimensional thermal resistance.

The main improvement in the heat sink design was the modifications to the fin array. In the design of the original heat sink, the thermal resistance of the fin array was calculated to be 0.515 W/M-K, with an overall fin efficiency of 82.1. The original heat sink had nine internal fins. To increase the efficiency of the fin array, the width of the heat sink was increased to incorporate more fins. The new heat sink has fourteen tapered internal fins fully exposed to air flow. The new heat sink design has a lower fin efficiency than that of the original design due to the thicker fins (76.8%). The thermal resistance of the fin array however is much less than the resistance of the original design, being calculated to be 0.205 K/W. The result of this design change was an improved overall thermal resistance of 0.261 K/W, providing faster heat dissipation to the ambient air.

The base mold design was not significantly simplified due to the failure of the soldered junction assemblies. Minor cost savings were gained by changing the heat sink design. The new extrusion is easier to produce since the fluid passageways are not enclosed.
6.2. Recommendations

Further analysis and re-design of the heat sink design is recommended, in order to optimize the base mold system. While the performance increased, the new heat sink design still has room for improvement. Production requirements resulted in the modified heat sink design being accepted for implementation in the beta testing machine before the optimization had been completed.

Improved methods for the compression-mounting of the TEC should also be evaluated in order to simplify the mechanical complexity of the base mold assembly. The toe clamps used for supplying the compressive force can, if over-tightened, break the corners of the TEC.

However, based on the results detailed in section 5.9, further experimentation with TEC soldering is not recommended. The soldering procedure offers few avenues for improvement. Without a newly designed TEC module more resistant to thermal fatigue or elevated assembly temperature, the use of a soldered thermoelectric cooler will not be possible.
Bibliography


Smith Alpheus W. Thermal, Electrical and Magnetic Properties of Alloys. The Engineering Experiment Station of the Ohio State University. Columbus, Ohio 1921.


A. Appendix: Test Procedures

The test procedures for the experiments performed during the course of this project are detailed in this Appendix. The experimental procedures are listed in order of in which they were performed. These procedures were developed in the course of experimentation, and represent the final revision of the test procedures.

A.1. Thermocouple Construction Procedure

A.1.1. Objective

This procedure specifies the proper method for constructing thermocouple wires for the direct measurement of temperature; it is intended to standardize the way the wires are produced, and to reduce error associated with improperly constructed thermocouples.

A.1.2. Materials and Test Equipment

- Thermocouple wire, J or T type.
- Needle Nose Pliers or Tweezers.
- Laser welder
- Crawford Precision Products model 500-4004 or equivalent.

A.1.3. Construction of Thermocouple Wire

1. Cut thermocouple wire into desired length.
2. Strip wire insulation from cut end approximately 1/8-3/16".
3. Using pliers or tweezers, carefully bend wire tips together so that they can be welded.

![Figure A-1. Tip Alignment](image)

4. Turn on laser welder.

5. Set voltage to 260V for T type thermocouple wire, set voltage to 245V for J type.

6. Set frequency to 2Hz.

7. Set pulse length to 1.3ms.

8. Carefully hold wire while welding, avoid direct skin contact with laser beam.
   a. Begin applying laser to wire junction.
   b. It may require a few moments until wires are hot enough to melt.
   c. When properly joined, there should be a ball of melted metal forming the junction.
9. Turn off laser welder when completed.

10. Strip lead ends for attachment to thermocouple reader.

11. Label thermocouple wire.

   a. For calibration purposes, use label maker to label wires. The label should include the thermocouple wire number, laboratory notebook number, and page number where calibration values are written.

   b. Number thermocouples sequentially for the experiment in which they were used. If needed for a later experiment, they can be easily referenced back to the recorded calibration data based on the notebook and page information printed on the label.

A.2. Thermocouple Calibration Procedure

A.2.1. Objective

This procedure was developed in order to create a standardized method for calibrating thermocouples for the direct measurement of temperature.

A.2.2. Materials and Test Equipment

- Thermocouple wire constructed following procedure detailed in section 1 of this Appendix.

- Dry Well Thermal Calibration Device (Hart Scientific Dry Well model 9102HDRC (or equivalent)).
c. Instrument Accuracy: ±0.5°C.

d. T Type thermocouple wire accuracy: Greater of ±1°C or 0.75% of reading.

- Aluminum well insert (0.30, 0.125, or 0.25)
- Thermocouple Readers
- Data acquisition system connected to computer equipped with serial port and Thermocouple Reader program. E.g. Cyber Research 4018 8-channel Thermocouple Module, Cyber Research 4520 RS-232 to RS-485 Converter, and +12V power supply, Dell latitude CP Laptop.

A.2.3. Procedure

1. Connect lead end of thermocouple to Data Acquisition System (DAS). Multiple thermocouples can be attached to DAS for simultaneous calibration.

2. Place welded junction of thermocouple wire into the aluminum insert inside the dry well. Three inserts are available, 1/8” diameter, 1/16” diameter, and 0.030” diameter.

3. Once the dry well temperature has settled at the desired set point, record the temperature sensed by the thermocouple connected to the DAS.
4. For each temperature setting, record set point value of dry well, as well as sensed temperature.

5. Calibration should be performed for a minimum of four data points spread throughout the expected range of the temperature measurement. Read operation manual for calibration device to determine the operational temperature range of the device.

6. Repeat steps 1 to 4 for each thermocouple requiring calibration.

A.2.4. Evaluation of calibration Data

1. Calculate the difference between the set point temperature and the sensed temperature for each temperature setting. If the difference remains relatively constant, the thermocouple is useable.

2. Average the difference between the dry well temperature and the sensed temperature. The average will be used as a correction factor for adjusting the sensed temperature to give a better approximation of the actual temperature.

<table>
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</tr>
<tr>
<td>62.2</td>
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<tr>
<td>Avg. Temp. Diff.</td>
</tr>
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</table>

3. The calibration data shown in Table A-1 demonstrates a useable thermocouple, since the average difference between the dry well temperature and the sensed temperature does not vary significantly for each calibration temperature.
4. If the thermocouple is found to have a large deviation between the sensed and calibrated temperature for each set point temperature, the temperature junction needs re-welded in order to form a better connection.

A.3. **Base Mold Assembly Procedure**

A.3.1. **Objective**

The objective of this procedure is to specify how to assemble the heat sink properly. The assembly is not difficult, but must be performed correctly in order to ensure proper operation.

A.3.2. **Required Equipment**

- Digital torque meter. Mark 10 model m6T50 or equivalent.
- Standard SAE Allen wrench set.
- Denatured alcohol wipes.
- (2) Melcor model HT8-12-40 thermal electric coolers.
- (4) Melcor model TSI-PAL-159-174 paraffin/aluminum interface pads.
- Model 2404-13-043 Large tissue base mold.
- Model 2404-13-044 Biopsy base mold.
- Model 2404-13-051 Fan Spacer.
- (2) JMC Datech model 5215-12HHBA 12V DC Fans.
- (8) Model 2404-13-041 Toe Clamps.
- (4) 1/16" diameter x ½" lg. dowel pins.
- Arbor press.
A.3.3. Assembly Procedure

1. Press in the locating pins for base mold alignment. The pins are pressed into the heat sink using the arbor press. When correctly pressed, the locating pins should protrude approximately $3/8''$ from the surface of the heat sink.

2. Clean component surfaces using denatured alcohol pads.
   
   a. Clean TEC mounting surfaces on heat sink.
   
   b. Clean lower surface of base mold.
   
   c. Clean upper and lower surfaces of TEC.
   
   d. Clean component surfaces using denatured alcohol pads.

3. Remove the thermal interface pad from its wrapping and place it onto the first cutout of the heat sink.

4. Place the TEC onto a thermal interface pad, positioning the TEC into the cutout so that the leads face the left side of the heat sink.

![TEC Alignment](image)

Figure A-4. TEC Alignment

5. Place the second thermal interface pad onto the upper surface of the TEC.

6. Locate the large tissue base mold on the locating pins. The shelf surface should point toward the exit end of the heat sink.

7. Press the base mold downward until it makes contact with the thermal interface pad.
8. Adjust the TEC and thermal interface pads so that the edges of the TEC and base mold are aligned.

9. Install and lightly tighten toe clamps on shelf side of the base mold:
   a. The toe clamps are fastened using (2) #6-32 x 3/8" long button head cap screws. Tighten using 1/16" Allen wrench.
   b. Check tightness of the two screws using the digital torque meter. The torque applied should be no more than 1 in-lb.

10. Repeat Steps 3 to 9 for the biopsy base mold, which mounts in the second position on the heat sink.

11. Install and loosely tighten the center two toe clamps.

12. The center two toe clamps bridge the two base molds.

13. Install and loosely tighten the rear two toe clamps on the biopsy base mold.

14. Tighten all toe clamps to final torque of 3 in-lbs. This should be done evenly, and in stages.
   a. First tighten all screws to a torque of 2 in-lbs.
   b. Tighten all screws to a torque of 3 in-lbs.

15. The thermal interface pad on the upper side of both TECs will protrude.

   Remove excess thermal interface pad material carefully with razor knife.

16. Attach thermal fuses:
   a. Clean the flat surfaces of the base mold edges with Loctite #701 primer.
   b. Using Loctite 401 or 420 adhesive, glue 82°C thermal fuse to left side of the base mold surface.
17. Use Loctite 401 or 420 adhesive to glue the RTD to right side of base mold, as shown in Figure A-6.

18. Using 5/64" Allen wrench, insert and tighten four #4-40 x 1" socket head cap screws through the fan plenum to the heat sink. Assemble one plenum to each end of the heat sink.

19. Using 3/32" Allen wrench, insert and tighten four #8-32 x 1" button head cap screws through the fan to the fan plenums. Assemble one fan to each end of the heat sink.

20. The direction of the air flow should be parallel. The airflow should exit at the side nearest to the standard large tissue base mold.
A.4. Initial Base Mold Test Procedure

A.4.1. Objective

The purpose of this experiment series is to define a highly repeatable test set-up and procedure that measures the response of the complete base mold assembly to heating and cooling, with and without a paraffin load. This must be designed in such a way that the results are easily comparable to the control.

A.4.2. Materials and Test Equipment

- Test Base Mold Assembly (record all components name, part number, and serial number).
- Laboratory DC power supplies (2) (i.e. Tenma variable output P/N 72-2080, Power-One +15V/+5V/-5V/-15V P/N MAP80-4003).
- 4-pole, 2-position switch (X-switch).
- Data Acquisition System (DAS).
- Cyber Research 4018 8-channel Thermocouple Module, Cyber Research 4520 RS-232 to RS-485 Converter, and +12V power supply
- PC, equipped with serial port and T/C Reader program.
- Multiple T-type thermocouple wires.
  a. Wire accuracy: greater of ±1°C or 0.75%
- Constant volume paraffin dispenser (modified syringe record volume required for test).
- Molten paraffin (VIP Embedding/Sectioning Medium at approximately 65 °C).
- Laboratory scale (i.e. Denver Instrument XE-100).
- Standard or Biopsy cassette Frames (virgin, record p/n, revision, and color)
- Fluke model 77II multi meters (2).
b. Voltage accuracy ±0.3% + 1 significant digit.

c. Current accuracy ±1.5% + 2 significant digits.

- Hart Scientific Dry Well model 9102HDRC.
- Loctite #701 primer and #420 adhesive.
- Hand held thermocouple reader model HH21, J-type thermocouple.

**A.5. Equipment Setup**

**A.5.1. Power Setup**

See Figure A-7:

1. Using the Tenma laboratory power supply, wire the master and slave in parallel so that the TEC load will not be current limited.

2. Put X-switch inline in order to switch the TEC between heating and cooling.

![Figure A-7. Power Diagram](image)

**A.5.2. Paraffin Setup: Constant Volume Dispenser**

In order to dispense the same amount of molten paraffin in each trial, a syringe was modified to draw up a consistent volume. The same volume must be dispensed
during each cycle so the TEC will see the same load. To achieve the measured
volume, the plunger of the syringe was drawn up to the designated volume.

The constant volume dispenser is set to dispense a volume of approximately
3.0ml. This corresponds to a mass of approximately 2.5g.

A 1/8 inch hole was drilled through the syringe body and plunger. This point would
become the upper limit. The holes in the syringe body were then slotted back toward
the dispensing end. When assembled, a 1/8" x 1 1/2" pin was placed through the hole
drilled in the plunger. The pin then followed the slot as the plunger was drawn back or
dispensed.

Blocks of paraffin may be formed by dispensing shots of molten paraffin into the
base mold and then cooling the paraffin to its solid state. The scale will be used to
measure the paraffin mass to quantify what minimal variation may exist

A.5.3. Thermocouple Setup

1. Only calibrated thermocouples may be used in this procedure.

2. Place one thermocouple at the entrance of the heat sink. This can be held in
place with electrical tape.

3. Place one thermocouple at the exit of the heat sink. The thermocouple can be
held in place with electrical tape.

4. One thermocouple is to be placed away from the heat sink to record the
ambient room temperature. For better results two can be used and averaged.
The ambient temperature thermocouples must be placed in a location where
heat from the power supplies or air from the fan will not distort the reading.

5. Clean the base mold surface at the RTD location (between the two holes on
the lower surface) using Loctite #701 primer. Use Loctite #420 adhesive to
glue the thermocouple to the base mold at the RTD location.
A.5.4. Procedure, Initial setup

1. Temperature in the room must be maintained at 22 ± 2°C.

2. Warm dispenser in paraffin bath (reservoir of molten paraffin)

3. With X-switch on heat, power TEC to heat to control point. Allow 1.5 minutes to reach steady state. Do not exceed 2.5 minutes of heat to avoid excessive energy in the system.

4. Begin recording temperature data. With no changes to the system during the first 30 seconds of data collection, the data from each channel may be averaged to find the variation in steady state.

5. Record paraffin temperature in dispenser immediately prior to dispensing. Dispense 3.0 ml of paraffin into base mold for duration of approximately 5 seconds. Record dispense time.

6. Switch TEC to cool immediately after dispense has completed. Continue to collect data while cooling for 3.5 minutes.

7. Weigh paraffin block that was extracted from base mold.
A.6. Continuous Base Mold Test Procedure

A.6.1. Objective

The purpose of this test procedure is to define a standard approach for continuous cycle testing of the base mold assembly. This test may be performed using the standard or biopsy base molds, and can be used with or without the cassette.

A.6.2. Materials and Test Equipment

- Test Base Mold Assembly (record all components name, part number, and serial number)
- Laboratory DC power supplies (2) (i.e. Tenma variable output P/N 72-2080, Power-One +15V/+5V/-5V/-15V P/N MAP80-4003)
- 4-pole, 2-position switch (X-switch)
- Data Acquisition System (DAS)
- CyberResearch 4018 8-channel Thermocouple Module, CyberResearch 4520 RS-232 to RS-485 Converter, and +12V power supply.
- PC, equipped with serial port and T/C Reader program.
- Multiple T-type thermocouple wires.
  a. Wire accuracy: greater of ±1°C or 0.75%.
- Constant volume paraffin dispenser (modified syringe record volume required for test).
- Molten paraffin (VIP Embedding/Sectioning Medium at approximately 65°C).
- Laboratory scale (i.e. Denver Instrument XE-100).
- Standard or Biopsy cassette Frames (virgin, record p/n, revision, and color).
- Fluke model 77II multi meters (2).
b. Voltage accuracy ±0.3% + 1 significant digit.

c. Current accuracy ±1.5% + 2 significant digits.

- Hart Scientific Dry Well model 9102HDRC.
- Temperature accuracy: ±0.5°C.
- Loctite #701 primer, and #420 adhesive
- Hand held thermocouple reader model HH21, J-type thermocouple

A.7. Equipment Setup

A.7.1. Power Setup

1. Using the Tenma laboratory power supply, wire the master and slave in parallel so that the TEC load will not be current limited.

2. Put X-switch inline in order to switch the TEC between heating and cooling. See Figure A-8.

Figure A-8. Power Diagram
A.7.2. Paraffin Setup

Constant volume dispenser: In order to dispense the same amount of molten paraffin in each trial, a syringe was modified to draw up a consistent volume. The same volume must be dispensed during each cycle so the TEC will see the same load. To achieve the measured volume, the plunger of the syringe was drawn up to the designated volume.

![Constant Volume Dispenser](image)

Two typical volumes used are 3.0 ml and 6.25 ml. 3.0 ml can be used in either the biopsy or standard base mold. 6.25 ml corresponds to approximately 5g of paraffin. This is typical of the amount dispensed into the standard base mold during machine operation.

A 1/8 inch hole was drilled through the syringe body and plunger. This point would become the upper limit. The holes in the syringe body were then slotted back toward the dispensing end. When assembled, a 1/8" x 1 1/2" pin was placed through the hole drilled in the plunger. The pin then followed the slot as the plunger was drawn back or dispensed.
Blocks of paraffin are formed by dispensing shots of molten paraffin into the base mold and then cooling the paraffin to its solid state. The scale will be used to measure the paraffin mass to quantify what minimal variation may exist.

A. 7.3. Thermocouple Setup

1. Only calibrated thermocouples may be used in this procedure.

2. Place one thermocouple at the entrance of the heat sink. This can be held in place with electrical tape.

3. Place one thermocouple at the exit of the heat sink. The thermocouple can be held in place with electrical tape.

4. One thermocouple is to be placed away from the heat sink to record the ambient room temperature. For better results two can be used and averaged. The ambient temperature thermocouples must be placed in a location where heat from the power supplies or air from the fan will not distort the reading.

5. Clean the base mold surface at the RTD location (between the two holes on the lower surface) using Loctite #701 primer. Use Loctite #420 adhesive to glue the thermocouple to the base mold at the RTD location.

A. 7.4. Procedure, Initial setup

1. Temperature in the room must be maintained at 22 ± 2°C.

2. Set data acquisition system to record for all cycles (minimum of 5). Each cycle consists of 30sec warm up and 3 minutes 30 seconds cooling time. The program will stop the recording once the desired data has been acquired.

3. Mark cycle number on frame with magic marker.

4. Weigh virgin frames on scale, record on data sheet or notebook.

5. Use the system clock on the computer to read the time.

6. Place dispenser in paraffin bath to warm. When warm, fill with paraffin. Note: After a while, exposure to the paraffin will cause the rubber boot on the
syringe to swell, causing a decrease in paraffin volume. If this occurs, replace the boot with one from a new syringe.

7. Turn on TEC power supply to heat up the TEC.

8. Place non weighed frame in base mold and dispense paraffin from the syringe into the base mold.

9. Switch the TEC to cool, and adjust the voltage to read a steady state value of 5.80±.05 VDC. Steady state voltage will occur when the block is nearing freezing.

10. Once the block is removable, turn off TEC, and switch to heat. Remove the paraffin block and discard.

11. Re-fill dispenser with paraffin from the reservoir.

12. Place the J-type thermocouple wire from the hand held unit into the tip of the syringe and place back in paraffin bath.

13. Use the lasso taped to the paraffin reservoir to keep the syringe from sliding and submerging in paraffin.


A.7.5. Procedure, Experiment

1. Place first frame into base mold.

2. Turn on TEC and data acquisition system once clock reaches zero seconds.

3. Allow Base mold and frame to heat for 30 seconds.

4. During last 4-5 seconds of heat time, dispense constant volume of paraffin into the base mold. Write down dispense temperature, and time base mold was heated for.

5. Immediately switch TEC to cool. Allow to cool for 3 minutes 30 seconds.

6. Hold down frame for approximately 10-15 seconds, from beginning of dispense.
7. Record steady state current and voltage.

8. Re-fill syringe, place thermocouple in tip. Place in paraffin bath and close door.

9. When cooling time is over, quickly pop paraffin block and frame out of base mold, switch TEC to heat and place in new weighed frame.

10. Place paraffin filled frame in scale. Record weight.

11. Repeat this procedure from step 3 for the desired number of trials.

A.8. Final TEC Soldering Procedure

A.8.1. Equipment Required

- Weller WES50 soldering station & PES50 soldering iron.
- Adjustable Variable Transformer with grounded outlet.
- New Weller soldering iron tip.
- Melcor #520016-00 93°C CdSnIn Eutectic solder.
- Melcor #CP-1.4-127-045 t/t (93°C solder) TEC.
- Copper Plated Base mold WE# 2404-13-043 rev B.
- Copper Plated Heat sink WE# 2404-13-060.
- General purpose acid flux.
- New coarse bristle acid brush.
- Electric fan.
- Thermolyne model F30430CM programmable oven (or equivalent).
- Steel weights.
- Cooling fan.
A.8.2. Procedure

Initial attempts at soldering the assembly following the instructions detailed on the Melcor web page were not successful. This method was developed through contact with Melcor technical support 1-609-393-4178.

Fit the Weller WES50 soldering iron with either a new tip, or one which is used for the CdSnIn Solder. It is important that the soldering tip not be contaminated by different composition solder. Contamination could lead to problems due to the low soldering temperature required for the TEC module.

Do not mix tips that were used with other types of solder. The locating pins used for positioning the base mold were pressed into position on the heat sink. If the locating pins do not press in tightly to the heat sink, use Loctite to secure the pins.

The programmable oven was turned on and set to 100°C. The oven was allowed to the steady state temperature. The base mold and heat sink were placed in the oven along with the two steel weights. Once the oven reached the steady state temperature, the heat sink was removed from the oven and placed on a wood board. The heat sink was fluxed using general acid flux. The soldering iron was then used to spread the solder evenly across the base mold mounting position.

Once wetted, it was placed back in the oven, and the base mold was removed. The base mold surface was fluxed, and the soldering iron used to spread the solder. After being fluxed, it was placed back in the oven.

The TEC surface does not need to be tinned, because the manufacturer was asked to do this. Clean the TEC surface with denatured Alcohol. The TEC was located on the heat sink. The milled pocket where the TEC mounts is offset with
respect to the central long axis of the heat sink. This was done due to the geometry of the model HT TEC that is currently used. Place the model CP such that leads face the left side of the heat sink.

![Figure A-10. TEC Location](image)

Place the base mold onto the TEC. The base mold is aligned with two pins. Place the two steel weights onto the base mold. Place assemble back into the oven. It is important that the TEC not be exposed to temperatures above \(80^\circ C\) for long periods of time since the internal solder will begin to break down.

Monitor the assembly. Do not leave it in oven for more than 10 minutes. Once the assembly is at temperature, the solder will begin to flow out of the gaps above and below the TEC. Once the solder flows, remove assembly from oven. Place on thermally insulating material. Cool assembly with fan set on low. It is important that the TEC is not cooled rapidly. If the cooling rate is too large, the TEC will fracture. Allow assembly to cool until it reaches ambient temperature. Shut off the oven and remove all materials from inside.
A.9. Calibration Data for Thermocouples

In the following tables, each thermocouple is designated by a number, and each number is assigned to a location.

A.9.1. Standard Base Mold Test

This test is discussed in Chapter 5, section 5.2.

Table A-2. Thermocouple Calibration: Standard Base Mold Test

<table>
<thead>
<tr>
<th>Locations</th>
<th>1a</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet: 2</td>
<td>SP</td>
<td>Reading</td>
<td>SP</td>
</tr>
<tr>
<td>Exit: 3</td>
<td>10.1</td>
<td>9.51</td>
<td>10.1</td>
</tr>
<tr>
<td>Amb.: 4 &amp; 5</td>
<td>25</td>
<td>24.4</td>
<td>25</td>
</tr>
<tr>
<td>RTD: 1a (m/m), 6 (CPL)</td>
<td>50.2</td>
<td>49.58</td>
<td>50</td>
</tr>
<tr>
<td>62</td>
<td>61.45</td>
<td>62.2</td>
<td>61.61</td>
</tr>
<tr>
<td>Mean Diff.: 0.59</td>
<td>Mean Diff.: 2.91</td>
<td>Mean Diff.: -1.7025</td>
<td></td>
</tr>
</tbody>
</table>

Table A-3. Thermocouple Calibration: Continuous Base Mold Test I

<table>
<thead>
<tr>
<th>Locations</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>Inlet: 2</td>
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<td>Reading</td>
<td>SP</td>
</tr>
<tr>
<td>Exit: 3</td>
<td>10.1</td>
<td>10.13</td>
<td>10.1</td>
</tr>
<tr>
<td>RTD: 1a (m/m), 6 (CPL)</td>
<td>50.2</td>
<td>49.97</td>
<td>50</td>
</tr>
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<td>62.1</td>
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<td>Mean Diff.: 0.165</td>
<td>Mean Diff.: -0.2325</td>
<td>Mean Diff.: -0.1425</td>
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</tbody>
</table>

A.9.2. Continuous Base Mold Test I

This test is discussed in Chapter 5, sections 5.4 and 5.5.

Table A-3. Thermocouple Calibration: Continuous Base Mold Test I

<table>
<thead>
<tr>
<th>Locations</th>
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<th>3</th>
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<tbody>
<tr>
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<td>Reading</td>
<td>SP</td>
</tr>
<tr>
<td>30.1</td>
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<td>29.69</td>
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<tr>
<td>62</td>
<td>62.09</td>
<td>62.1</td>
<td>62.02</td>
</tr>
</tbody>
</table>
### Locations
- **Inlet:** 2
- **Exit:** 3
- **Amb.:** 4 & 5
- **RTD:** 1d (Soldered), 6 (CPL)

#### A.9.3. Continuous Base Mold Test II

This test is discussed in Chapter 5, section 5.3.

Table A-4. Thermocouple Calibration: Continuous Base Mold Test II

|-----------|-------------------|----------------|----------------|----------------|

#### Locations
- **Inlet:** hcc4-157-31
- **Exit:** 2-157-29
- **Amb.:** 4-157-29
- **RTD:** 12-157-39
A.9.4. *Voltage Performance Test*

This test is discussed in Chapter 5, section 5.4.

Table A-5. Thermocouple Calibration: Voltage Performance Test

<table>
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<th>Locations</th>
<th>Mean Diff.: 0.01</th>
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<th>Mean Diff.: 0.15</th>
<th>Mean Diff.: 0.0425</th>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Exit:</strong> 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Amb.:</strong> 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RTD:</strong> 1A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>