ThermoClamp®-3 and -3.2 Temperature Controller

User's Manual

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AUTOMATE SCIENTIFIC

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The ThermoClamp® is intended for research use only.

Table of Contents

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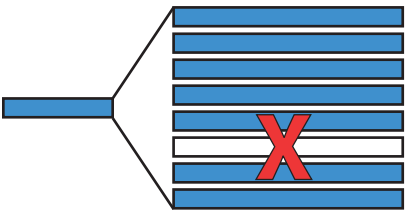
Table of Contents Continued

NO EMPTY TUBES!

ALL tubes of the Perfusion Pencil MUST be filled with solution before starting every experiment, even if they are not being used. Otherwise liquid will flow backwards into the empty tubes, then leak out and CONTAMINATE the other solutions later.



Introduction

FOR RESEARCH USE ONLY
The ThermoClamp is designed for solution-switching use in research applications ONLY. AutoMate Scientific, Inc. cannot be responsible for injury or death resulting from medical or pharmacological use.

Packing List

Item	Quantity
ThermoClamp®-3 or -3.2 temperature controller	1
Heated Perfusion Pencil® manifold	1
Bath thermocouple	1
Power supply (12V DC)	1
This ThermoClamp user manual	1

This equipment must be earth grounded using the post on the back of the controller.

CE

Features and specifications

ThermoClamp-3 Controller

- Auto-tuning PID (Proportional Integral Derivative) temperature control accurate to <1.0°C (often ±0.1˚C) with fuzzy logic
- Extremely low noise (analog heating) designed for electrophysiology
- Over-temperature protection
- Three types of user-configurable thermal runaway protection (patent pending) with fuzzy logic constraints
- Smart voltage setpoint: digital, analog (BNC) or automatic
- Separate displays for both temperatures (control sensor and safety sensor)
- Constant USB/serial data stream output
- Automatic heater failure detection and prevention
- Utilization of the safety sensor as secondary input for feedback control

Perfusion Pencil® Inline heater

- 1, 4, or 8 channels for solution heating with flow rates up to 5cc/min @ 37˚C
- Temperature controlled bath perfusion inline heating with a flow rate up to 5cc/min
- Small manifold volume for rapid switching
- Temperature can be maintained for the entire bath, or just for solutions being delivered
- Perfusion Pencil tips are interchangeable / replaceable with standard AutoMate tips

Electronic specifications

- Power supply: 100-240V AC, 50-60 Hz input; 12V, 5A output
- Heater output: 2 channels at quiet analog 0-12V up to 1A = 24 Watts total
- Front panel BNC output voltage (to record the temperature): 40mV/deg C
- Front panel input voltage (to control the setpoint): 20 deg C/V
- Serial baud rate: 230400
- Safety TC limit: 75˚C (adjustable)
- Max setpoint: 65˚C
- Default setpoint: 35˚C (adjustable)

Acronyms, abbreviations and definitions

CU	ThermoClamp Controller unit
Isopotential	Grounding (earth) point
PID	Proportional Integral Derivative
TC	Thermocouple (temperature sensor)

This equipment must be earth grounded using the post on the back of the controller.

Components

Controller unit

The Controller Unit (CU) is shown in Figures 1 and 2. The integrated temperature controller and power supply for the heater are the main components of the controller unit.

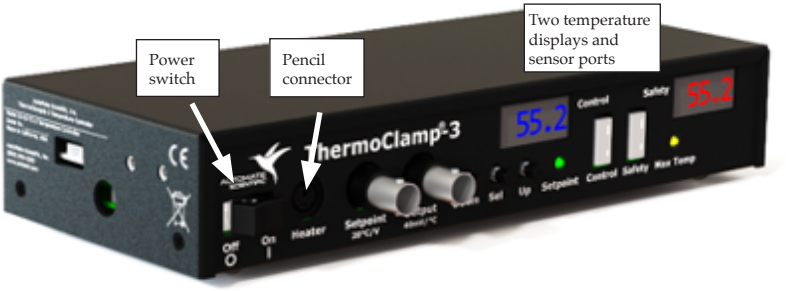


Figure 1. Controller unit, front view

The sensor plugged-in to the “Control” port is used to control the temperature. The thermocouple in “Safety” is just used to prevent overheating of the Pencil. If you only use one sensor, connect it to "Safety."

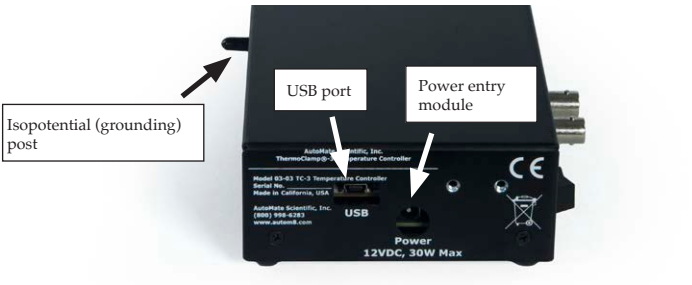


Figure 2. Controller Unit, rear view.

NOTE: The ThermoClamp-3 and its heated Perfusion Pencil should both be grounded for high-gain electrophysiology.

Perfusion Pencil®

The Heated Perfusion Pencil® (Pencil) manifold is shown in Figures 3, 4 and 5. The actual heating of the solutions happens in the Pencil. The optional bath solution is also heated as it flows through the Pencil.

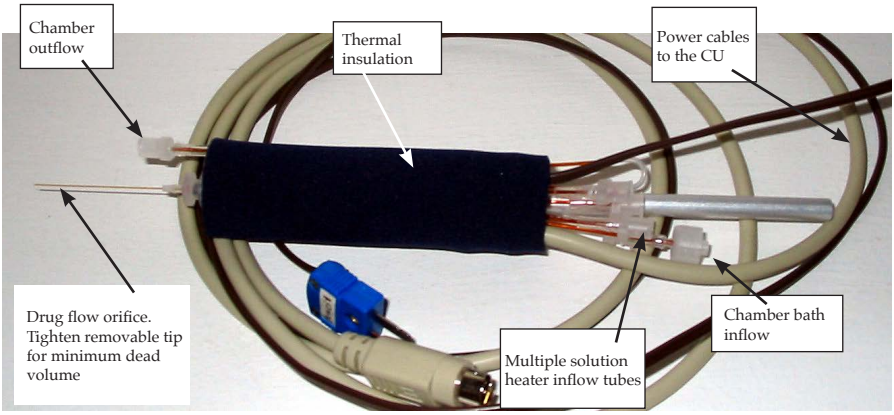


Figure 3. Side view of the Perfusion Pencil.

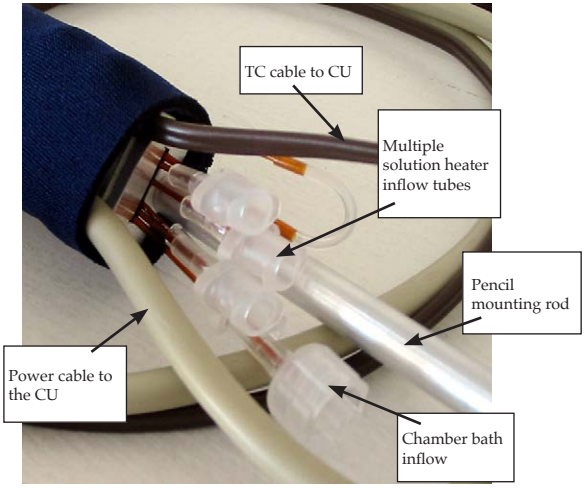


Figure 4. Detailed view of the rear part of the Perfusion Pencil.

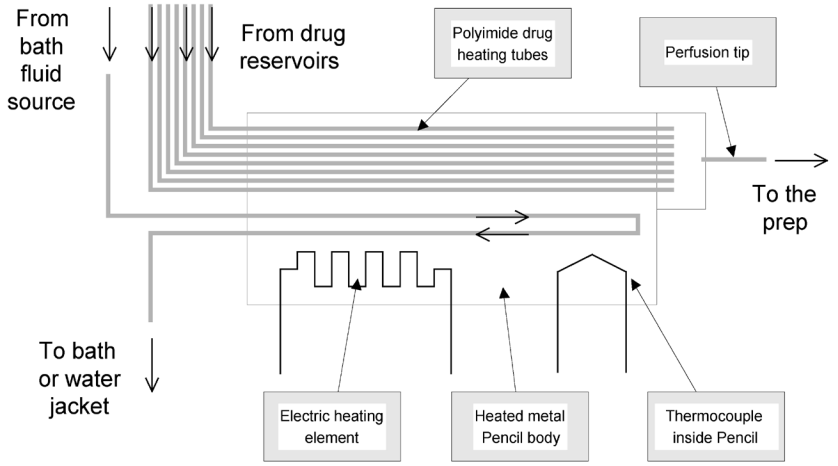


Figure 5. Heated Perfusion Pencil schematic.

Perfusion Pencil Placement

Your Heated Perfusion Pencil must be placed as close as possible to the perfusion chamber. If it is too far away, the liquid in your tubes will lose all of its heat before it reaches the chamber. The maximum distance between the Pencil and chamber depends on a number of variables including: tubing material (thermal conduction), fluid dripping versus flowing into the perfusion chamber via submerged tube, and ambient temperature and drafts. You may be able to mount your Pencil farther from the chamber if you try double-tubing – use a piece of large Tygon tubing as thermal insulation outside a small piece of Teflon tubing. Make sure your solution flows into your chamber rather than dripping. The extra exposure to cool room air will greatly decrease the delivered liquid temperature. Finally, avoid placing your chamber in a location where it is regularly blown by air drafts. Many researchers purchase or build enclosures around their chambers or entire microscopes to help control the temperature and avoid air drafts.

Bath Perfusion / Water Jacket Feature

The Heated Perfusion Pencil includes an extra tube for heating a flowing bath solution. This heated high-flow line will maintain the bath temperature while quickly washing-out drugs applied through the tip. The Pencil can maintain at least 37˚C with flow rates of 5cc/min.

This extra line can also be used with a water jacket on certain perfusion chambers. A "water jacket" is usually a separate chamber or bath outside a perfusion chamber for circulating a heating or cooling liquid. The perfusion chamber must be equipped with a water jacket. It is not usually something that can be added later. Simply provide a high flow of water from a large reservoir through the Pencil, into the chamber's water jacket, and out to a drain or recirculating pump for ideal heating.

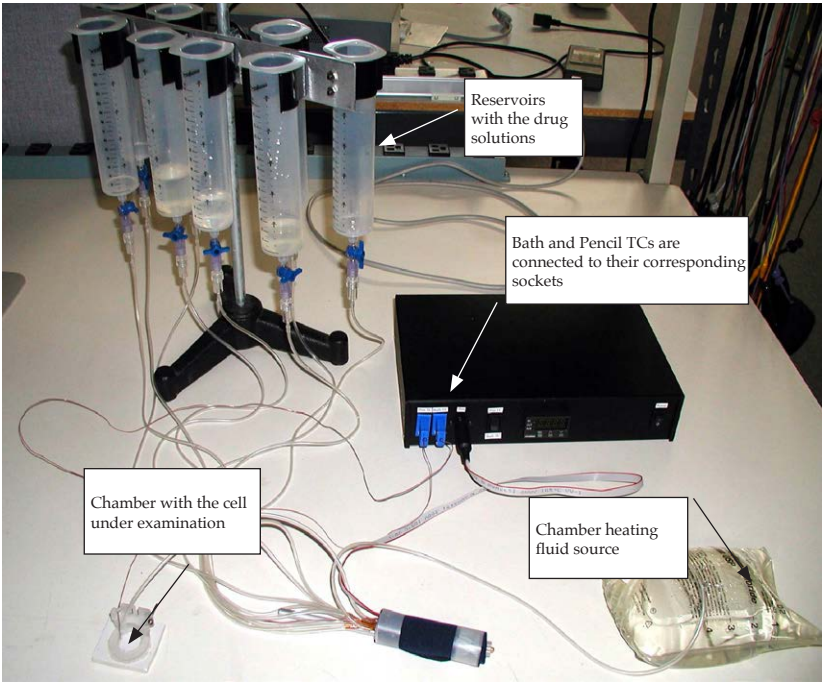


Figure 6. Set up example of ThermoClamp temperature controller and accessories.

Chemical Information

The tubing inside the manifold body is polyimide (nylon) coated with PTFE. Additional connection tubing is silicone. The removable tips include a medical-grade polypropylene Luer-lock fitting with a fused silica (quartz) needle coated with polyimide outside and PTFE inside. These materials are resistant to most acids, bases and organic solvents. To avoid dust contamination, we recommend pre-rinsing the Perfusion Pencil and tip with distilled water. Also, it is good practice to discard the first few microliters of solution before using the device. The Heated Perfusion Pencil and removable tips are shipped non-sterile. The Pencil can be chemically sterilized with cleaning solutions in each line. The removable tips can be chemically sterilized or autoclaved. However, repeated autoclaving may weaken the adhesive bond between the luer-lock fitting and the needle.

Making sure the device works properly

1. Connect the Pencil connector to the ThermoClamp control box (CU).
2. Connect the Pencil thermocouple plug to the Safety TC socket.
3. Connect the bath thermocouple plug to the Control TC socket (if used.)
4. Connect the tubes to their valves and reservoirs. Notice the fragile capillaries.
5. Warning: Do not leave any solution tubes at the rear of the Perfusion Pencil unconnected.
6. Fill and plug any unused tubes on the rear of the Perfusion Pencil with solution to prevent backflow and cross-contamination.
7. Connect the power cable to the CU via power entry module.
8. Ground the CU using the grounding post on the rear face, and the Pencil.
9. Turn on the on the CU power switch. The temperature controller should display the ambient temperature. If the “Pencil Max Temp” LED lights or the red "Safety" display shows "Err", check the Safety thermocouple plug. If the blue "Control" temperature display is blank, check the Control thermocouple plug (if used).
10. Adjust the setpoint above the ambient temperature. (Refer to the section on adjusting the setpoint.) The controller will start heating the Pencil. If the controller has not been autotuned, the temperature will probably overshoot. (Refer to the section on autotuning the temperature controller.)
11. To verify that the Pencil does not leak internally, open the bath perfusion flow and all of the delivery valves. Look for leaks at each end of the Pencil.

Getting Started

1. The Bath sensor (if used) is plugged-into the "Control" TC port, and the thermocouple built-into the heated Perfusion Pencil™ manifold or QuickStage™ heated perfusion chamber (with brown wire) connects to the "Safety" TC jack. The blue LED display (left) shows the bath temperature. The red display (right) is the safety temperature. If you do not wish to use the bath sensor, then it should be unplugged. Then the ThermoClamp will keep the Pencil or chamber at the set temperature using only their internal sensor.

2. Set your desired temperature digitally or with the analog voltage input BNC connector. To set it digitally, press the "Set" button once, briefly, and the "Setpoint" LED will illuminate. Use the left, blue display to set your desired temperature. Click or hold the Up or Down buttons until the desired setpoint is displayed. If you don't press anything for a few seconds, then the green light will turn off and the blue display will show the actual bath temperature again. The maximum setpoint is 65˚C.

3. You can also use the analog input with a voltage from your computer to set the setpoint. This input uses 20 deg C/V. Therefore, give the ThermoClamp's BNC input a voltage of +1.6 V for a 32˚C setpoint. Then you can also use your computer to change it.

4. Since it has both digital and analog setpoints, the ThermoClamp auto-selects which one to use. If you don't connect anything to the analog input, then the controller will use the digital setpoint. If you connect an analog voltage to the input, then the controller automatically uses it. It is possible to override this automatic selection by selecting "Digital" or "Analog" setpoint mode in the settings menu (see settings menu section for details). You will see the displays update briefly when the mode changes. The system defaults to "Auto".

5. One of the cool features of the ThermoClamp controller is thermal runaway protection. If you are using a bath temperature sensor and you turn your perfusion flow off, then the bath will start to get cold. Previous controllers will try to increase the stage or inline heater temperature, but the bath temperature will continue to drop. This is called "thermal runaway." This is why our heaters all include a Safety sensor - so they will only increase to about 75˚C before they stop heating any further. While this may protect the

equipment, it is probably undesirable to expose your cells to this maximum temperature. This ThermoClamp-3 detects when runaway is happening (perfusion stops or the sensor is removed from the chamber), and it holds the heater temperature constant until the bath sensor starts warming up again. This should make it much easier to turn perfusion off or temporarily remove the bath sensor. This new feature is so unique, we applied for a patent.

6. The controller will also detect when perfusion flow may have stopped unexpectedly and the bath sensor is cooling slowly over time. This will also trigger an error state that protects the system from driving the inline heater or QuickStage up to its maximum temperature (Fig. 7).

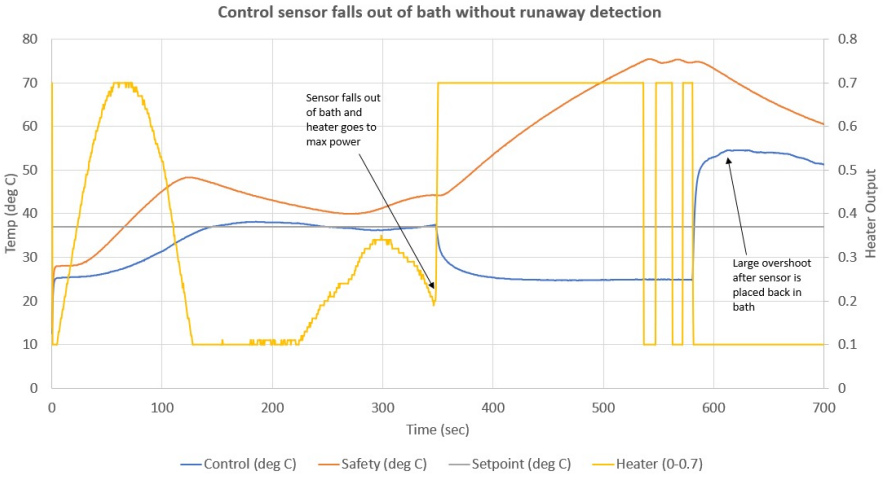


Figure 7. This graph shows the temperature controller with thermal runaway protection turned OFF. The "Control" sensor is placed in a bath of water which is electrically heated by the ThermoClamp. You can see the bath temperature represented by the blue line was near the desired 37˚C Setpoint from time 150 to 350 seconds when the Control sensor is removed from the bath to simulate a user purposely or accidentally removing it. The temperature controller doesn't know the sensor was removed. It simply sees the temperature drop steeply at time 350 sec, so it quickly ramps-up the heater until its Safety sensor reaches a maximum of 75˚C (orange line). When the Control sensor is returned to the bath around time 575 seconds, one can see that its temperature has also risen well over the Setpoint which would have permanently damaged the experiment.

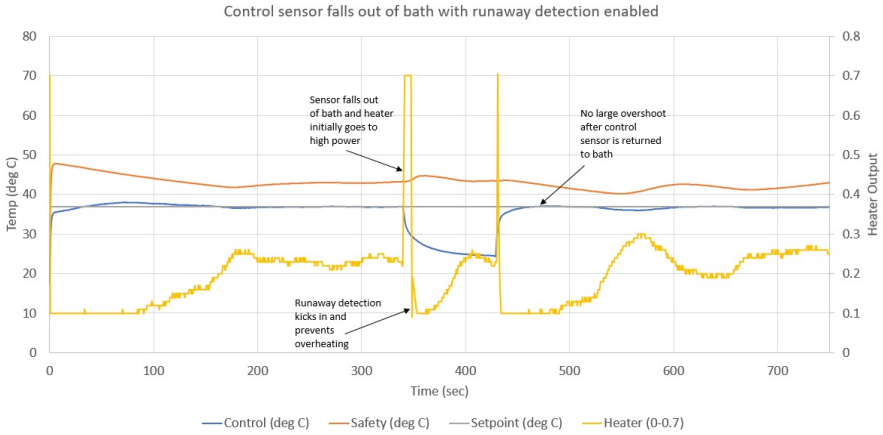


Figure 8. This second graph shows the temperature controller with thermal runaway protection turned ON. Again, the blue line shows the Control sensor in the bath at the desired 37°C Setpoint temperature until it is removed around time 340 seconds. The temperature controller again believes that the bath temperature has dropped, and rapidly increases the heater output. However, this time it recognizes that the bath temperature is not increasing, and the Safety sensor shows that the heater is warming. From this information, it deduces that something has gone wrong and thermal runaway has begun. Instead, it switches to maintaining the heater's old temperature as measured by the Safety sensor (orange line). Later, when the Control sensor is returned to the bath, one can see that it was kept near the 37°C Setpoint without overshoot or damage (blue line).

7. When the controller detects thermal runaway or stopped flow, it will show a letter "E" before the blue bath temperature. It will watch for the bath temperature to rise again, and automatically disable the error when the sensor starts warming. **If the controller mistakenly detects runaway or you return the sensor to the bath quickly after the error shows up and it doesn't clear itself, then you can reset it manually by clicking the Up or Down button.**

8. Run-away detection is enabled by default, showing an "E" in the LED output when the control temp moves in the opposite direction it's expected to move based on heater's output, or when it doesn't change when it's expected to. The sensitivity of these error detection modes can be adjusted in the settings menu, and they can also be disabled by setting ESF or ESB sensitivity to zero (ESB = runaway, ESF = stopped flow), or by setting the (E LO = low temperature) threshold to its maximum value of 15.0.

8.1 If you start testing with the default settings and too many errors are being triggered in your test setup, then the first step is to decrease ESF until you no longer get unwanted "stopped flow" errors, since this is the most sensitive of the three error detection algorithms.

8.2 If low-temperature errors persist after stopped flow errors have been reduced, then increase the "E LO" parameter in the settings menu to reduce the low-temperature error sensitivity.

8.3 After adjusting "ESF" and "E LO" as described, you can control the speed at which the system will detect rapid cooling of the bath sensor (falling out of the bath) by adjusting the "ESB" value. A higher ESB value will cause the system to more quickly detect errors, and a lower "ESB" will result in fewer false positive errors.

9. The yellow "max temp" LED only comes on when the safety TC reaches its max value (adjustable, default = 75˚C). This is not dangerous, and the ThermoClamp and heated Pencil can both exist at this temperature indefinitely.

10. The controller includes a bi-directional USB port on the side. It can be used to update the firmware on the ThermoClamp or output a constant stream of data on temperatures, input/output voltages, power, etc.

Settings Menu

1. The ThermoClamp includes a settings menu that can be accessed by pressing and holding the "Sel" button for at least 3 seconds. Once the controller enters the settings menu, it will briefly display "Set Adj" on the blue and red LED displays until the "Sel" button is released.

2. When the system is in the settings menu, the "Sel" button can be used to switch to the next parameter, and the "Up" and "Down" buttons can be used to adjust the value of each parameter. The parameter names will be displayed on the blue (left) LED display, and the value of the parameter will be displayed on the red (right) display. For example, (blue) = SPED (red) = FAST means that the SPED parameter is selected with a current value of FAST.

3. If the controller detects that nothing has been changed for 10 seconds, then it will store the current settings to its non-volatile memory and

leave settings mode. It will also leave settings mode if the “Sel” button is used to cycle through all of the available parameters and the end of the settings menu is reached.

4. The following parameters can be adjusted, with the format of [parameter name]:[value] (value with *asterisk is the default):

   4.1 **[SPED]:[FAST, *NORM, SLOW, AUTO]**
   This Speed setting adjusts the parameters (gains) used for PID control. AUTO are the gains resulting from autotuning the controller (explained in Chapter 4). The NORM gains are preset values that should work well for smaller water baths or higher flow rates, where there isn’t much time delay between the heater turning on and the bath sensor warming up. The SLOW setting will work better for setups with large water baths or longer delays between the heater and bath, and FAST will work best when the bath sensor warms very quickly after the heater turns on.

   4.2 **[INPT]:[*AUTO, ANLG, DGTL]**
   This sets the input mode for the controller’s setpoint. AUTO will detect if an analog voltage is connected to the front panel "Setpoint" BNC connector and use it, otherwise it will use the digital setpoint. ANLG will force the analog setpoint to be used, even if nothing is connected to the BNC, and DGTL will force the digital setpoint to be used, even if an analog input is connected.

   4.3 **[TUNE]:[YES, *NO]**
   The TUNE parameter will start autotuning the controller if it is set to “YES,” and the controller exits the settings menu (either by timing-out after 10 seconds or after other parameters are adjusted). Autotuning will not run after exiting the settings menu if TUNE is set to “NO”. See chapter 4 for more information on auto-tuning.

   4.4 **[VERB]:[*ON, OFF]**
   The VERB (Verbose) parameter either enables the controller to output text diagnostic and error messages over its serial port (ON), or it disables text output from the controller (OFF). Disabling text output can be useful if data is being recorded in numerical format for post-processing and it is undesirable to mix text output in with the rest of the numerical data being recorded.

4.5 **[ESB]:[0,1,2,*3,4,5]**
The ESB (Error Sensitivity Bath) setting sets the error sensitivity level for bath sensor runaway detection. This is designed to detect when the bath sensor accidentally falls out of the bath, or is removed while changing cells/dishes. Setting it to 0 disables the error detection completely, and 1 is the least sensitive setting (so errors will not show up unless the bath sensor cools significantly when it's not expected to.) Setting the value to 3 results in nominal sensitivity, and setting to 4 or 5 will make the error detection more sensitive, allowing the controller to detect that something may be going wrong more quickly, but also increasing the chance that it gives false-positive errors when the bath sensor warms and cools slightly during normal testing.

4.6 **[ESF]:[0,1,2,*3,4,5]**
The ESF (Error Sensitivity Flow) setting sets the error sensitivity level for stopped flow detection. This detects when the bath sensor cools slowly over a long period of time when the controller wouldn't expect it to do so (usually because perfusion flow stops). Setting it to 0 disables the error detection completely, and 1 is the least sensitive setting with the error enabled. Setting the value to 3 results in nominal sensitivity, and setting to 4 or 5 will make the error detection more sensitive, allowing the controller to detect that something may be going wrong more quickly, but also increasing the chance that it gives false-positive errors when the bath sensor warms and cools slightly during normal testing.

4.7 **[SAFE]:[50.0…85.0]**
The SAFE parameter adjusts the maximum temperature limit for the heater. This is the upper limit for the safety temperature at which the heater power is turned off, no matter what. The safety temperature may continue to rise above this maximum temperature as heat continues to spread in the QuickStage or inline heater after the power is shut off, but no current flows to the heater transistors when the system is above this maximum temperature and the yellow "Max Temp" LED is illuminated. Default is 75.0˚C.

4.8 **[Curr]:[0.5…1.2]**
The Curr (Max Current) parameter sets the maximum current (Amps) that the controller outputs per channel at the maximum software command. This is an approximate upper limit, and the heater channel currents will typically be slightly below this upper maximum during operation. Default is 0.9 Amps. Using a lower maximum current setting slows the heating rate and may improve performance if there

is a large time delay between the heater being powered and the bath sensor warming, but setting Curr too low will increase the chance that the system detects overcurrent and displays errors over the serial port as it adjusts its output to stay below the maximum current level.

4.9 **[E LO]:[3.0…15.0]**
The "E LO" (Error Low Temp) parameter defines a threshold temperature band below the setpoint that will trigger an error if the control sensor continues to cool slowly when it should be warming, even if it doesn't cool rapidly enough to generate an "ESF" or "ESB" error. When the control sensor temperature reaches a value of "E LO" less than the setpoint and it has been steadily cooling, then this error will occur. Setting the "ELO" parameter to a large value decreases its sensitivity, since this requires the control sensor to fall more before reaching the threshold temperature. Setting it to the maximum value of 15.0 will disable it completely. Its default value is 5˚C.

4.10 **[VER]**
The VER (Version) parameter is a read-only value that displays the current firmware running on the controller. It will be in the format of x.yy (eg. 1.25). After pressing "Sel" to move past the VER parameter, the system will exit the settings menu and return to normal operation, since it is the last parameter. The current firmware version is also printed out to serial immediately after the controller is powered on.

Monitoring the ThermoClamp from your computer

1. The ThermoClamp can be monitored by your computer and software using either the front-panel BNC port (temperature only) or the USB port (much more information). To use the BNC output, simply connect the BNC to your recording hardware (i.e. analog input on your digitizer) and record it alongside your other data.

   1.1 The output will give 40mV/deg C. For example, if the control (or safety sensor if no control) temperature is 30˚C, then the output voltage will be 1.2 V.

2. To use the USB port, connect a USB cable to monitor the output with a serial terminal program. You can use any serial software like *Realterm, SerialPlot* or *PlotLog* for Windows or *CoolTerm* for Mac OS. The serial baud rate is 230400.

   2.1 In *CoolTerm*, select "Options", "Serial Port." Set the Baud rate, and choose the Port – probably "usbmodem." Then click "Connect" to start watching the USB/serial data.

   2.2 Choose "Connection" menu : "Capture to Text/Binary File" to begin recording the output to a file.

3. You must use a quality "Type-B Mini" USB cable. Bad/defective cables can cause serial errors. Some USB cables are meant only for charging and do not include data wires. The controller should appear on your desktop (Mac) or in your system COM ports list (Windows) after it has been connected with a functioning cable.

4. When the ThermoClamp first powers on, it will print out a header that contains information about stored parameters, as well as the current firmware version. The following is an example of the power-on header followed by a description of each term (underlines added for clarity):

   Firmware_Version 1.24
   Setpoint 35.0
   Divergence_Limit 5.0
   PID_Mode AUTO
   AUTO_PID_Gains 1.500 0.003 0.00008 0.10000 7.000
   Setpoint_Mode AUTO
   Runaway_Sensitivity_ESB 3

Stopped_Flow_Sensitivity_ESF 3
Verbose_Errors On
Max_Current 0.80
Max_Hot 0.50 Max_Norm 0.62 Ch1_Max_(A) 0.65 Ch2_Max_(A) 0.61

Firmware_Version: Indicates the current firmware running on the controller

Setpoint: digital setpoint, in °C units

Divergence_Limit: This is used for error detection and will be updated when the controller gains are autotuned from the settings menu.

PID_Mode: This indicates which mode the controller is using to control its output (either FAST, NORM, SLOW or AUTO)

AUTO_PID_Gains: This displays the PID gains resulting from the last time the controller was autotuned. If autotuning has never been performed, then the values will stay at default levels.

Setpoint_Mode: Either AUTO, ANLG or DGTL. This can be changed in the settings menu.

Runaway_Sensitivity_ESB: This number (0-5) can be changed in the settings menu. It determines the sensitivity of runaway error detection. Set it to 0 to disable this error detection mode, set it to 3 for nominal sensitivity, or increase it to 5 for maximum sensitivity (and the highest chance of unwanted errors from showing up during your experiment).

Stopped_Flow_Sensitivity_ESF: This number (0-5) can be changed in the settings menu, and it determines the sensitivity of stopped flow error detection. Set it to 0 to disable this error detection mode, set it to 3 for nominal sensitivity, or increase it to 5 for maximum sensitivity (and the highest chance of unwanted errors from showing up during your experiment).

Verbose_Errors: Either On or Off. This determines whether text output is enabled for diagnostic and error messages and can be changed in the settings menu.

Max_Current: This is the current level through each heater channel that the system will target at maximum software command, aiming to

keep the actual current slightly below the max. It can be adjusted in the settings menu.

Max_Hot: This is the maximum software command determined from a power-on test of the controller's hardware that is expected to keep the current below maximum when the safety temperature is toward the high end of its range. It will always be a lower value than the "Max_ Norm" command, since the heater current increases as it gets hotter at a given software command value.

Max_Norm: This is the maximum software command determined from a power-on test of the controller's hardware that is expected to keep the current below maximum when the safety temperature is toward the low end of its range. It will always be higher than the "Max_Hot" value and less than or equal to 1.0.

Ch1_Max_(A): This is the actual current measured through the controller's current sense resistor on the first channel during the brief power-on test that measures heater channel sensitivity. It will be lower than the maximum current because it is measured when the heater transistors are cool and at their lowest sensitivity.

Ch2_Max_(A): This is the actual current measured through the controller's current sense resistor on the second channel during the brief power-on test that measures heater channel sensitivity. It will be lower than the maximum current because it is measured when the heater transistors are cool and at their lowest sensitivity.

5. The controller constantly outputs seven columns of space-delimited data over the serial USB port in the following format, every ½ second (500 msec). The space-delimited format makes it easy to copy and paste the data into spreadsheet software for subsequent analysis:

```
Control Safety Setpoint Heater I1 I2 Runaway
21.2 24.9 32.0 0.55 0.63 0.59 0
22.8 25.0 32.0 0.54 0.63 0.59 0
23.7 25.1 32.0 0.53 0.61 0.57 0
24.2 25.2 32.0 0.51 0.60 0.56 0
24.5 25.4 32.0 0.50 0.57 0.55 0
24.7 25.5 32.0 0.49 0.56 0.54 0
24.9 25.7 32.0 0.48 0.53 0.51 0
```

If the system is in an error state, then the word "Error" will be added on to the end of each line of data to make it obvious that something is going wrong. If that happens, you'll see something like this:

21.2 24.9 32.0 0.55 0.63 0.59 1 Error
22.8 25.0 32.0 0.54 0.63 0.59 1 Error
23.7 25.1 32.0 0.53 0.61 0.57 1 Error

Control = Control temperature (°C) (always equals zero if unused)
Safety = Safety temperature (°C)
Setpoint = Setpoint temperature (°C)
Heater = Heater output (0-1.0 with no heat generated below 0.18)
I1 = Current through first heater channel (Amps)
I2 = Current through second heater channel (Amps)
Runaway = Error state (0 for no error, 1 for error)

6. When monitoring the controller from your computer, it will output the following serial error messages if it detects something a problem:

6.1 **Overcurrent detected and max_command_normal reduced to 0.xx**
This means that the controller detected current higher than the maximum level defined in the settings menu when the safety temperature is toward the lower end of the range and it reduced the software limit in response. This can happen normally and isn't something to worry about unless it starts showing up frequently.

6.2 **Overcurrent detected and max_command_hot reduced to 0.xx**
This means that the controller detected current higher than the maximum level defined in the settings menu when the safety temperature is toward the upper end of the range and it reduced the software limit in response. This can happen normally and isn't something to worry about unless it starts showing up frequently.

6.3 **Heater malfunction - shut the system down.**
This message is only displayed after the controller detects excessive current and tries to reduce its software limits below reasonable values. This will typically only occur when a heater transistor fails short or its mounting screw comes loose. If this error gets displayed, then the heaters are disabled and you'll need to restart the controller to turn them back on.

6.4 **Runaway detected @ divergence = xx.y**
This error occurs when the controller detects that the bath sensor may have fallen out, or the flow rate may have changed unexpectedly and caused the bath sensor to cool rapidly. The sensitivity of this error detection mode can be adjusted via the "ESB" parameter in the settings menu.

6.5 **Stopped flow detected @ divergence = xx.y**
This error occurs when the controller detects that flow may be blocked between the heater and the bath, or that the control sensor may be slowly losing thermal contact with the bath fluid. The sensitivity of this error detection mode can be adjusted via the "ESF" parameter in the settings menu.

6.6 **Control sensor is warming - no longer in error state.**
This message will be displayed when the system recovers from an error state because it detects the control sensor warming up again after it is put back in the bath or flow resumes after previously being stopped.

6.7 **Low temp error - control temp too far below setpoint.**
This message will be displayed with the control sensor temperature is steadily falling below the setpoint and the "E LO" error is triggered.

Autotuning

1. The ThermoClamp includes its own autotuning routine to pick control parameters (gains) that are well-suited to each particular test setup. If both the control (bath) sensor and safety sensors are being used, then it autotunes the system using the control sensor temperature. If only the safety sensor is plugged in, then it uses that to perform the autotuning.

2. To start autotuning, first let the controller stabilize near the desired setpoint, since tuning will be most effective this way. Autotuning works best if you use it while the entire system including microscope stage, perfusion flow, any external heaters, etc. are all functioning like they will during normal use.

3. Hold the "Sel" button for at least 3 seconds to enter the settings menu, and then press "Sel" to move through the parameters until "TUNE" is displayed on the blue (left) LED display. Press either the "Up" or "Down" button once to change the default "No" value to "Yes", and then wait 10 seconds for the settings menu to time out and exit. The system will immediately start autotuning when it leaves the settings menu and "TUNE" has been set to "Yes".

4. The controller will display an "A" on each LED display during autotuning, and it will warm and cool the system while measuring the response on the sensors. This will normally only take about 5 minutes, but it could take up to 20 minutes for slow systems. If the controller can't perform its tuning routine in 20 minutes, then it will time-out without setting new control gains.

5. During autotuning, the controller will send a slightly different format of serial data output to the computer. It will look like the following six columns, where the "Time" channel displays the number of seconds that have elapsed since the start of autotuning and the "Runaway" error state is not displayed. The other channels are the same as the normal serial output:

   Time Control Safety Heater I1 I2
   0.0 31.7 33.4 0.18 0.004 0.000
   0.5 31.7 33.4 0.80 0.854 0.802
   1.0 31.7 33.4 0.80 0.874 0.812
   1.5 31.8 33.5 0.80 0.892 0.818

6. At any time during autotuning, you can press the "Down" button to immediately exit back to normal operation without setting new control gains.

7. After successfully completing the autotune routine, the system will no longer display the "A" before each temperature on the segment LED displays, and it will go back to normal operation. The new gains will be stored, and the system will set itself to "AUTO" PID mode.

8. At the end of the autotune routine, the controller will print out a fuzzy logic "System Category" classification over the serial port if VERB is set to "On" in the settings menu. This is for diagnostic purposes and summarizes the measured response of the test setup:

System Category	Response
1	Fast with low overshoot
2	Very fast response
3	Slower without much overshoot
4	Fast with significant overshoot
5	Moderately Slow with significant overshoot
6	Slow or with substantial time delay
7	Very Slow

9. If the controller detects that something went wrong during the autotuning process, then it may output one of the following errors on the segment LED displays or serial port:

   9.1 **Auto Err**
   This will be displayed on the segment LEDs any time the system aborts without setting new control gains.

   9.2 **Bad gain**
   This will be displayed on the segment LEDs if the system completes the autotune routine, but the control gains were range-limited because unreasonable values were calculated. The controller will set the new gains in this case, but they probably won't be ideal, so you'll want to re-tune or use one of the static modes (FAST, SLOW, NORM).

9.3 **Autotune error: control warming during cool-down phase.**
This will be printed over the USB serial port if the system aborts the autotune process because the control sensor was warming up when it should have been cooling, likely due to changing flow rates or the sensor moving to a different sampling location.

9.4 **Autotune error: control cooling during warm-up phase.**
This will be printed over the USB serial port if the system aborts the autotune process because the control sensor was cooling down when it should have been warming, likely due to changing flow rates or the sensor moving to a different sampling location.

9.5 **Safety TC at max temp limit for xx sec. Exiting auto-tune without changing gains.**
This will be displayed if the safety sensor stays above the maximum temperature limit for too long during autotune (xx = seconds). The system will abort autotune if this happens. The controller will not be able to warm the bath sensor above the starting temperature if the safety sensor starts near maximum temperature, so the autotuning routine requires that the safety sensor stay below max temp to accurately measure the system's response. If you are working with a system that has a large temperature difference between the heater and bath sensors, then you can try autotuning at a lower setpoint to prevent the safety sensor from reaching max temp, then just increase the setpoint again after autotuning.

9.6 **Invalid safety temperature error - autotune will abort without setting new gains.**
This will be displayed if the safety sensor comes unplugged or stops generating valid readings during the autotune process. The controller cannot operate without a functioning safety sensor.

If any errors occur that prevent the autotune process from finishing and setting new gains, then the controller's LED display will show "Auto Err" until either the Up or Down button is pressed to clear the error. If "Auto Err" is displayed on the controller, then it has *NOT* set new control gains for the AUTO mode.

LED Display error codes

1. As previously mentioned in this manual, the ThermoClamp will display an **"E"** on the Control LED display if it is currently in an error state, and the **"E"** will go away when the control sensor warms and the system leaves the error state.

2. If the system detects excessive current in either of the heater channels after it has made several attempts to incrementally reduce the software control limits, then it will completely shut the heaters off and display an **"H"** on the safety LED display, with the yellow Max Temp light flashing. The only way to return from this error state is to power cycle the controller (turn it off and back on), but please check the heater before doing so, since there could be something wrong with the way the transistors are mounted, or a transistor could have failed.

3. The system always needs a safety sensor to be connected to operate, so it will display **"Err"** on the safety (right) LED display if no thermocouple is plugged into the Safety jack. The system will not power the heaters if the Safety sensor is unplugged.

4. If any errors occur that prevent the autotune process from finishing and setting new gains, then the controller's LED display will show "**Auto Err**" until either the Up or Down button is pressed to clear the error. If "Auto Err" is displayed on the controller, then it has NOT set new control gains for the AUTO mode.

Updating firmware over the USB Port

1. The controller's firmware can be updated over the USB port by dragging and dropping a new .bin file onto the device when it is connected to a computer and appears as a COM port (Windows) or a removable drive on your Desktop (Mac):

   1.1 Connect the ThermoClamp's power supply and turn it on.

   1.2 Connect the controller to the computer with a quality "Type-B Mini" USB cable. Bad/defective cables can cause serial errors, and some USB cables are meant only for charging and don't include data wires. The controller should appear on your desktop (Mac) or in your system COM ports list (Windows) after it has been connected with a functioning cable.

   1.3 Drag the .bin file with new firmware from your PC onto the controller's drive (Mac) or COM port device (Windows). Ignore the "Disk Not Ejected Properly" error on Macintosh computers.

   1.4 Disconnect the USB cable when the transfer has finished.

2. If you tried to program the controller but see a "Not enough room" or similar error message appear when the file transfer starts, then you probably forgot to turn the controller on before connecting the USB cable to the computer. Try turning the controller off and back on again, and it should show up as a drive on the computer.

3. If the controller still doesn't show up but you have power-cycled it and the USB cable is connected, then you are most likely using a bad USB cable, or a USB cable that is designed for charging only.

4. After new firmware is programmed, you can confirm that it worked properly by monitoring the serial output at power-on to see the new version, or check the "Ver" parameter in the settings menu where it will display the new version number if programming worked.

Switching fluids

While fluid remains stagnant within the Heated Pencil, its temperature will climb higher than the setpoint. When you switch liquids, there will be a small temperature overshoot like the one shown in Figure 8 below. When all solution flow is stopped, the ThermoClamp tries to maintain the desired bath temperature by increasing heat to the Pencil. Without liquid flow, none of this added heat reaches the chamber, so the Pencil continues heating until the overtemp LED lights or the ThermoClamp detects the thermal runaway and stops overheating.

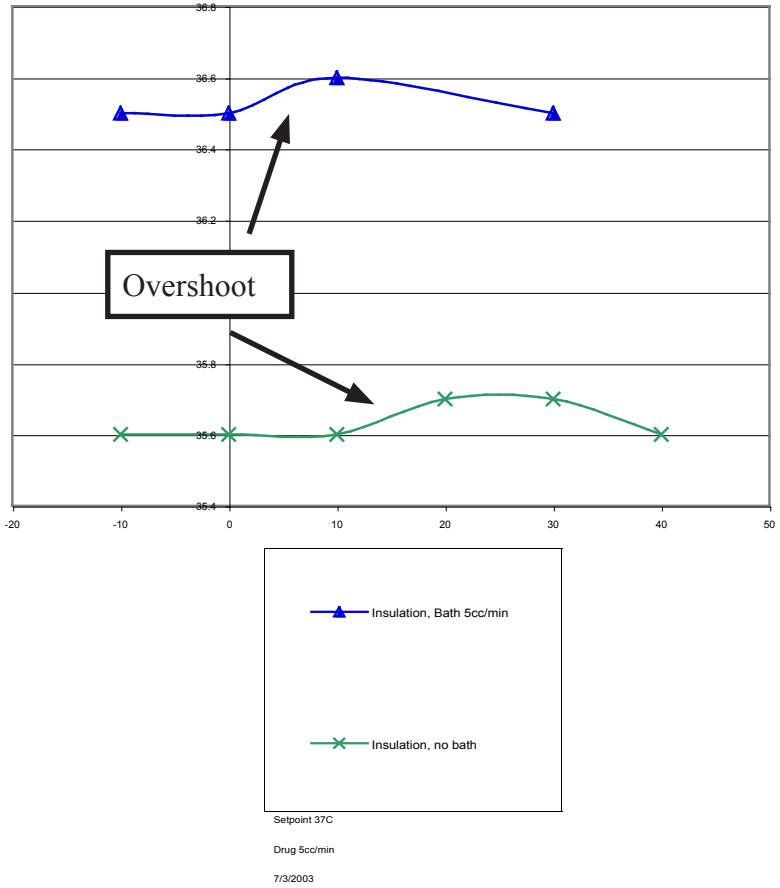


Figure 9. Temperature vs. Time curves for fluid switching

Operating without the bath sensor

When using an inline heater like the Perfusion Pencil, the bath thermocouple allows the ThermoClamp controller to monitor the bath temperature and heat your solutions in order to maintain the overall bath temperature. If you are using another controller to warm your bath (with stage, chamber or objective heaters, etc.), then you may not want the ThermoClamp to use the bath temperature for deciding whether to heat your solutions. If your other temperature controller is doing a good job, and you use a bath sensor, then the ThermoClamp will always think that its liquids are at the correct temperature, and will not apply any heat. Instead, it will be dispensing cold reagent into a warmed chamber!

If you use another controller to maintain your chamber/bath temperature, or you do not wish to use the ThermoClamp bath thermocouple, simply unplug it. This way the ThermoClamp will observe and maintain the temperature of the Pencil irrespective of the bath.

NOTE: The ThermoClamp will not operate (the "Max Temp" LED will light) if you try to use it without anything plugged into the Safety TC socket. Leave the Pencil's built-in sensor connected to Safety.

With the bath sensor removed, the temperature measured and displayed by the ThermoClamp will be the internal temperature of the Perfusion Pencil, not the temperature of your chamber bath. If you wish to maintain a particular bath temperature with flow from the Heated Pencil but without using the bath sensor, you will need to measure the difference between the bath temperature and stable Pencil temperature. Since the liquid will cool by several degrees before reaching the bath, you must set the Pencil temperature setpoint higher by the observed offset.

Maintenance

You can expect several years of useful lifetime for your tip if you wash it daily. Use a syringe or vacuum to pull water, then alcohol three times through the tip. If the Perfusion Pencil tip is filled with pure salt solution, leaving it in the syringe overnight will not usually cause the tip to block. However, if it is used for high viscosity fluids, flushing after each use is recommended.

Cutting the Pencil tips

The removable tips are shipped with 1.5" (3.8 cm) length polyimide needles. They are intended to be cut to a desired length by rolling a razor blade on them against a hard surface. However, this may leave a small crack or barb on the tip. To get a flat cut, score the coating of the needle with a ceramic cleaving stone or a diamond cutter and pull directly apart, making sure not to pull at an angle. You may notice a larger outer tube enclosing the lower part of our smaller, 100 μm needles. This is simply for added rigidity and can be cut if needed.

Max Temp LED

The ThermoClamp is equipped with a warning light to warn you of a high temperature inside the heater. If the "Max Temp" LED lights during use, it means that the heater has reached its maximum temperature. This is not necessarily a problem. All AutoMate devices are designed to operate indefinitely at Max Temp. The LED may illuminate while heating a cold perfusion chamber or cold perfusate. The Max Temp circuit will reset itself once the temperature drops. You do not need to do anything.

Here is an example of a Max Temp situation. If you leave the bath thermocouple sitting on a cold table while the ThermoClamp is running, the controller will think that the bath temperature is significantly below your setpoint. It will apply heat to the Pencil, but will not observe an increase in the "bath" temperature. It will continuing heating the Pencil indefinitely. The Max Temp Safety sensor automatically stops heating the Pencil and lights the indicator LED once the Pencil reaches a user-defined maximum.

Sensors

Several problems can arise with your ThermoClamp sensors. One of the simplest problems is having the bath sensor fall out of the bath. The bath sensor (if used) must be in good thermal contact with the bath solution. The insulation on the bath sensor can also degrade until the bath solution makes electrical contact with the thermocouple. If the blue Control display goes blank or shows a strange number, the bath sensor may be shorting to the bath solution. Try removing the sensor from the bath to see if the blue display reappears. Make sure you are not grounding the thermocouple with your fingers. If you suspect broken insulation on the thermocouple, dip it in epoxy and allow it to dry.

The thermocouples or their wires or plugs can break. This is easy to observe with a multimeter (ohmmeter) as an infinite resistance measurement. Check inside the sensor's blue plug for a loose screw. The sensors are simply two different thermocouple wires soldered together. Remove any oxidation build-up on the plugs.

It may be possible for the Pencil TC to short to the inside of the Pencil. This can be observed as a zero resistance between the Pencil TC plug (either lead) and the metal Pencil body. If you suspect a shorted Pencil TC, carefully remove the Pencil's "wetsuit." Remove two screws holding the top of the Pencil. You can see the Pencil TC at the end of its two wires. Dip the ends of the bare wires into some epoxy for insulation and allow to dry. Reassemble and test the Pencil.

The ThermoClamp-1 uses standard T-type thermocouples for bath and Pencil.

Finally, we wanted to mention that most digital voltmeter thermometers with thermocouples are only accurate to +/- 2°C. Unless you perform a multi-point calibration on your digital thermometer, it should probably not be trusted to calibrate your ThermoClamp.

Replacement Parts

Part No.	Description
04-360	360 μm Removable Tip
04-250	250 μm Removable Tip
04-100	100 μm Removable Tip
03-08-xxx	Heated Perfusion Pencil [8-channel with xxx size tip]
03-08	Replacement Heated Perfusion Pencil [8-channel]
03-01-j	ThermoClamp-3-1 Control Unit
03-22-j	ThermoClamp-3-2 Control Unit
03-sensor	Bath thermocouple sensor

Safety Instructions

The following instructions pertain to the risk of fire, electric shock, or bodily injury. Please read all of these instructions carefully.

1. Follow all the instructions and warnings marked on this product and included in this manual.

2. Do not use this product on an unstable cart, stand, or table. This product may fall, causing serious damage to the product.

3. Slots and openings in the cabinet and the back are provided for ventilation. To ensure the reliable operation of your product, and to protect it from overheating, these openings must not be blocked or covered. Do not use this product on a bed, sofa, rug or other similar surfaces. This product should never be placed near or over a radiator or heat register. This product should not be placed in a built-in installation unless proper ventilation is provided.

4. Never push objects of any kind into the product through the cabinet openings, as they may touch dangerous voltage points or short-out parts that could result in fire or electric shock. Never spill liquids of any kind in the product.

5. This product should only be connected to the AC power source indicated on your product system's information label. If you are not sure of the type of AC power available, consult your dealer or local power company. Only connect this product to a power outlet that matches the power requirements of this product.

6. Do not allow anything to rest on the power cord. Do not locate this product where people will walk on the cord.

7. If you have to use an extension cord with this product, make sure that the total amperage rating of all equipment plugged into it does not exceed the amperage rating of the extension cord. Also, make sure that the total of all products plugged into the main AC power outlet does not exceed 15 Amps.

8. Unplug your product from the main electrical power before cleaning. Do not use liquid cleaner or aerosol cleaners. Use a damp cloth for cleaning.

9. Do not use the controller near liquids except as instructed.

Unplug this product from the main power outlet and call for service under any of the following conditions:

A. If the power cord or plug is damaged or frayed.
B. If liquid has been spilled into the ThermoClamp controller.
C. If the product has been exposed to rain or water.
D. If the product has been dropped or the cabinet has been damaged.
E. If the product exhibits a distinct change in performance, indicating a need for service.

STOP!!

If you ever have to remove the main system unit cover, observe the following precautions:

A. The power supply cord must be unplugged before the main system unit cover is removed. (Separe le cordon d'alimantation et puis enleve le couvercle.)

B. Once removed, the cover must be replaced and screwed in position before the power supply is plugged back in. (Apres le couvercle en place et remettre le cordon d'alimentation.)

Warranty

AutoMate Scientific, Inc. warrants its products against defects of workmanship and/or material for ONE YEAR from the date of sale. Any product that fails to perform as specified may be returned, freight pre-paid to the factory (with a written explanation of the problem) for examination and repair or replacement. If it is defective, AutoMate Scientific will repair or replace (at our option) the product without charge and return it to you.

If the examination indicates that non-compatible fluid, destructive environment, accidental damage, modification or abusive practices have occurred, all labor, materials and freight costs shall be at the expense of the customer.

Due to the nature of clinical laboratory applications, AutoMate Scientific, Inc. will NOT accept the return of any products which have been used with HAZARDOUS MATERIALS or in a harmful environment. This warranty is in lieu of all other warranties, whether oral or written, express or implied. In no event shall AutoMate Scientific, Inc. or its licensor/licensees be liable for contingent, special, direct, indirect or consequential damages for the breach of any express or implied warranty or resulting from the use, failure or malfunction of any product, including damage to property and, to the fullest extent permitted by law, damages for personal injury, even if AutoMate Scientific, Inc. has been advised of the possibility of such damages or if this warranty is found to fail its essential purpose. AutoMate Scientific, Inc's liability is limited to the reimbursement of the cost of the product. All other warranties, including, but not limited to warranties for fitness or merchant ability for a particular purpose are expressly excluded. No verbal changes to this policy will be authorized.

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