2.4.2 Heater Location

For best temperature measurement accuracy the heater should be located so that heat flow between the cooling power and heater is minimized. For best control the heater should be in close thermal contact with the cooling power. Geometry of the load can make one or both of these difficult to achieve. That is why there are several heater shapes and sizes.

2.4.3 Heater Types

Resistive wire like nichrome is the most flexible type of heater available. The wire can be purchased with electrical insulation and has a predictable resistance per given length. This type of heater wire can be wrapped around a cooling load to give balanced, even heating of the area. Similar to sensor lead wire, the entire length of the heater wire should be in good thermal contact with the load to allow for thermal transfer. Heat sinking also protects the wire from over heating and burning out.

Resistive heater wire is also wound into cartridge heaters. Cartridge heater are more convenient but are bulky and more difficult to place on small loads. A typical cartridge is 1/4 inch in diameter and 1 inch long. The cartridge should be snugly held in a hole in the load or clamped to a flat surface. Heat sinking for good thermal contact is again important.

Foil heaters are thin layers of resistive material adhered to, or screened on to, electrically insulating sheets. There are a variety of shapes and sizes. The proper size heater can evenly heat a flat surface or around a round load. The entire active area should be in good thermal contact with the load, not only for maximum heating effect, but to keep spots in the heater from over heating and burning out.

2.4.4 Heater Wiring

When wiring inside a vacuum shroud, we recommend using 30 AWG copper wire for heater leads. Too much heat can leak in when larger wire is used. Heat sinking, similar to that used for the sensor leads, should be included so that any heat leaking in does not warm the load when the heater is not running. The lead wires should be twisted to minimize noise coupling between the heater and other leads in the system. When wiring outside the vacuum shroud, larger gage copper cable can be used, and twisting is still recommended.

2.5 CONSIDERATION FOR GOOD CONTROL

Most of the techniques discussed above to improve cryogenic temperature accuracy apply to control as well. There is an obvious exception in sensor location. A compromise is suggested below in Paragraph 2.5.3 – Two Sensor Approach.

2.5.1 Thermal Conductivity

Good thermal conductivity is important in any part of a cryogenic system that is intended to be at the same temperature. Most systems begin with materials that have good conductivity themselves, but as sensors, heaters, sample holders, etc., are added to an ever more crowded space, the junctions between parts are often overlooked. In order for control to work well, junctions between the elements of the control loop must be in close thermal contact and have good thermal conductivity. Gasket materials should always be used along with reasonable pressure.

2.5.2 Thermal Lag

Poor thermal conductivity causes thermal gradients that reduce accuracy and also cause thermal lag that make it difficult for controllers to do their job. Thermal lag is the time it takes for a change in heating or cooling power to propagate through the load and get to the feedback sensor. Because the feedback sensor is the only thing that lets the controller know what is happening in the system, slow information to the sensor slows the response time. For example, if the temperature at the load drops slightly below the setpoint, the controller gradually increases heating power. If the feedback information is slow, the controller puts too much heat into the system before it is told to reduce heat. The excess heat causes a temperature overshoot, which degrades control stability. The best way to improve thermal lag is to pay close attention to thermal conductivity both in the parts used and their junctions.

2.5.3 Two-Sensor Approach

There is a conflict between the best sensor location for measurement accuracy and the best sensor location for control. For measurement accuracy the sensor should be very near the sample being measured which is away from the heating and cooling sources to reduce heat flow across the sample and thermal gradients. The best control stability is achieved when the feedback sensor is near both the heater and cooling source to reduce thermal lag. If both control stability and measurement accuracy are critical it may be necessary to use two sensors, one for each function. Many temperature controllers including the Model 331 have two sensor inputs for this reason.

2.5.4 Thermal Mass

Cryogenic designers understandably want to keep the thermal mass of the load as small as possible so the system can cool quickly and improve cycle time. Small mass can also have the advantage of reduced thermal gradients. Controlling a very small mass is difficult because there is no buffer to adsorb small changes in the system. Without buffering, small disturbances can very quickly create large temperature changes. In some systems it is necessary to add a small amount of thermal mass such as a copper block in order to improve control stability.

2.5.5 System Nonlinearity

Because of nonlinearities in the control system, a system controlling well at one temperature may not control well at another temperature. While nonlinearities exist in all temperature control systems, they are most evident at cryogenic temperatures. When the operating temperature changes the behavior of the control loop, the controller must be retuned. As an example, a thermal mass acts differently at different temperatures. The specific heat of the load material is a major factor in thermal mass and the specific heat of materials like copper change as much as three orders of magnitude when cooled from 100 K to 10 K. Changes in cooling power and sensor sensitivity are also sources of nonlinearity.

The cooling power of most cooling sources also changes with load temperature. This is very important when operating at temperatures near the highest or lowest temperature that a system can reach. Nonlinearities within a few degrees of these high and low temperatures make it very difficult to configure them for stable control. If difficulty is encountered, it is recommended to gain experience with the system at temperatures several degrees away from the limit and gradually approach it in small steps.

Keep an eye on temperature sensitivity. Sensitivity not only affects control stability but it also contributes to the overall control system gain. The large changes in sensitivity that make some sensors so useful may make it necessary to retune the control loop more often.

2.6 PID CONTROL

For closed-loop operation, the Model 331 temperature controller uses a algorithm called PID control. The control equation for the PID algorithm has three variable terms: proportional (P), integral (I), and derivative (D). See Figure 2-3. Changing these variables for best control of a system is called tuning. The PID equation in the Model 331 is:

$$\text{Heater Output} = P\left[e + I\int(e)\,dt + D\frac{de}{dt}\right]$$

where the error (e) is defined as: e = Setpoint – Feedback Reading.

Proportional is discussed in Paragraph 2.6.1. Integral is discussed in Paragraph 2.6.2. Derivative is discussed in Paragraph 2.6.3. Finally, the manual heater output is discussed in Paragraph 2.6.4.

2.6.1 Proportional (P)

The Proportional term, also called gain, must have a value greater than zero for the control loop to operate. The value of the proportional term is multiplied by the error (e) which is defined as the difference between the setpoint and feedback temperatures, to generate the proportional contribution to the output: Output (P) = Pe. If proportional is acting alone, with no integral, there must always be an error or the output will go to zero. A great deal must be known about the load, sensor, and controller to compute a proportional setting (P). Most often, the proportional setting is determined by trial and error. The proportional setting is part of the overall control loop gain, and so are the heater range and cooling power. The proportional setting will need to change if either of these change.

2.6.2 Integral (I)

In the control loop, the integral term, also called reset, looks at error over time to build the integral contribution to the output:

$$Output\ (I) = PI\int (e)\, dt.$$

By adding the integral to proportional contributions, the error that is necessary in a proportional only system can be eliminated. When the error is at zero, controlling at the setpoint, the output is held constant by the integral contribution. The integral setting (I) is more predictable than the gain setting. It is related to the dominant time constant of the load. As discussed in Paragraph 2.7.3, measuring this time constant allows a reasonable calculation of the integral setting. In the Model 331, the integral term is not set in seconds like some other systems. The integral setting can be derived by dividing 1000 by the integral seconds: $I_{setting} = 1000 / I_{seconds}$.

2.6.3 Derivative (D)

The derivative term, also called rate, acts on the change in error with time to make its contribution to the output:

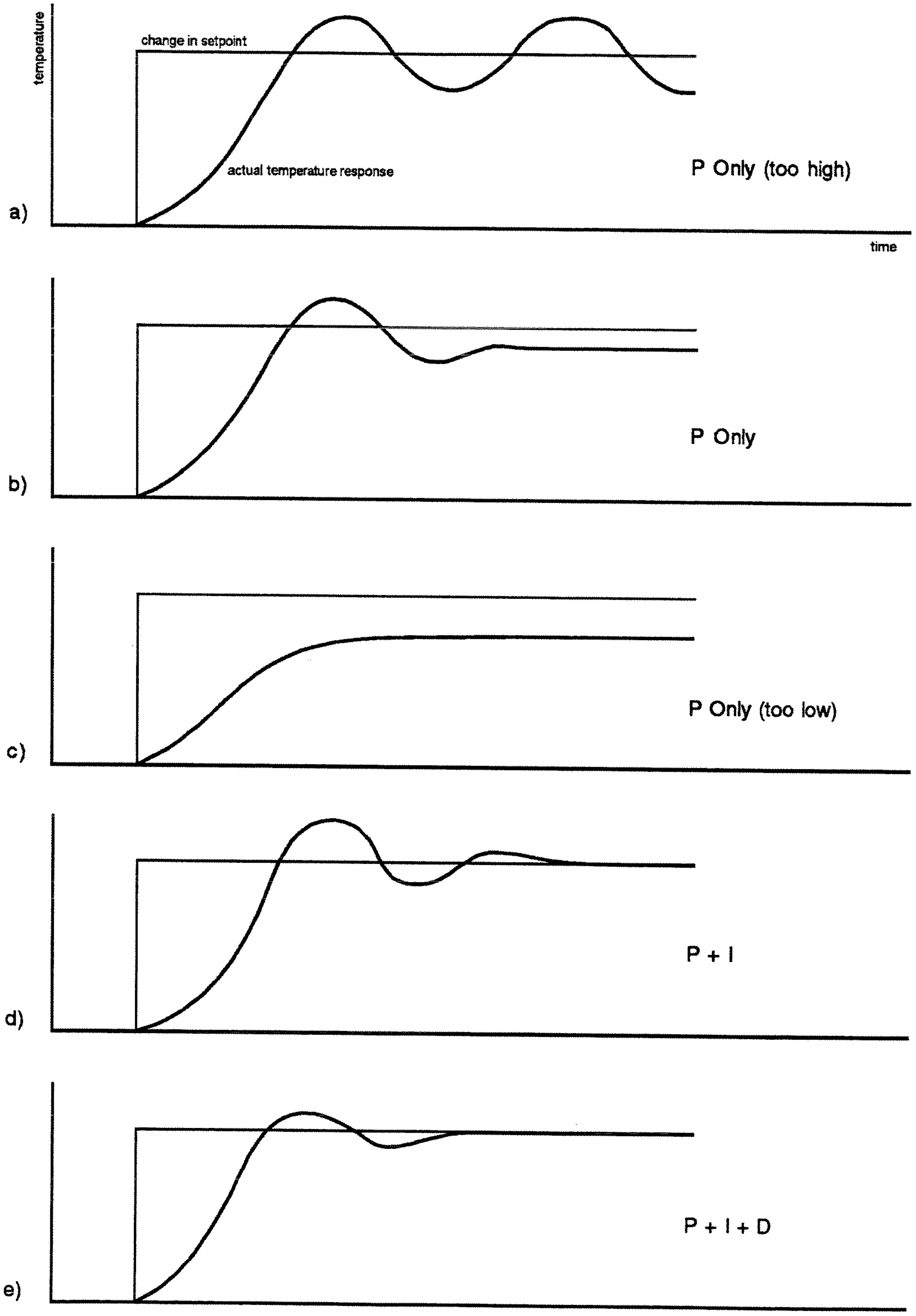
$$Output\ (D) = PD\frac{de}{dt}.$$

By reacting to a fast changing error signal the derivative can work to boost the output when the setpoint changes quickly, reducing the time it takes for temperature to reach the setpoint. It can also see the error decreasing rapidly when the temperature nears the setpoint and reduce the output for less overshoot. The derivative term can be useful in fast changing systems but it is often turned off during steady state control because it reacts too strongly to small disturbances. The derivative setting (D) is related to the dominant time constant of the load similar to the $I_{setting}$ and is therefore set proportional to $I_{setting}$ when used.

2.6.4 Manual Heater Power (MHP) Output

The Model 331 has a control setting that is not a normal part of a PID control loop. Manual Heater Power (MHP) output can be used for open loop control, meaning feedback is ignored and the heater output stays at the users manual setting. This is a good way to put constant heating power into a load when needed. The manual output term can also be added to the PID output. Some users prefer to set a power near that necessary to control at a setpoint and let the closed loop make up the small difference. MHP is set in percent of full scale current or power for a given heater range.

NOTE: MHP should be set to 0% when not in use.



P-331-2-3.bmp

Figure 2-3. Examples of PID Control

2.7 MANUAL TUNING

There has been a lot written about tuning closed loop control systems and specifically PID control loops. This section does not attempt to compete with control theory experts. It describes a few basic rules of thumb to help less experienced users get started. This technique will not solve every problem, but it has worked for many others in the field. This section assumes the user has worked through the operation sections of this manual, has a good temperature reading from the sensor chosen as a control sensor, and is operating Loop 1. It is also a good idea to begin at the center of the temperature range of the cooling system (not close to its highest or lowest temperature). AutoTune (Paragraph 2.8) is another good place to begin, and do not forget the power of trial and error.

2.7.1 Setting Heater Range

Setting an appropriate heater output range is an important first part of the tuning process. *The heater range should allow enough heater power to comfortably overcome the cooling power of the cooling system.* If the heater range will not provide enough power, the load will not be able to reach the setpoint temperature. If the range is set too high, the load may have very large temperature changes that take a long time to settle out. Delicate loads can even be damaged by too much power.

Often there is little information on the cooling power of the cooling system at the desired setpoint. If this is the case, try the following: Allow the load to cool completely with the heater off. Set manual heater output to 50% while in Open Loop control mode. Turn the heater to the lowest range and write down the temperature rise (if any). Select the next highest heater range and continue the process until the load warms up to room temperature. Do not leave the system unattended, the heater may have to be turned off manually to prevent overheating. If the load never reaches room temperature, some adjustment may be needed in heater resistance or load.

The list of heater range versus load temperature is a good reference for selection the proper heater range. It is common for systems to require two or more heater ranges for good control over their full temperature. Lower heater ranges are normally needed for lower temperature. The Model 331 is of no use controlling at or below the temperature reached when the heater was off. Many systems can be tuned to control within a degree or two above that temperature.

2.7.2 Tuning Proportional

The proportional setting is so closely tied to heater range that they can be thought of as fine and course adjustments of the same setting. An appropriate heater range must be known before moving on to the proportional setting.

Begin this part of the tuning process by letting the cooling system cool and stabilize with the heater off. Place the Model 331 in closed loop control mode with manual PID tuning, then turn integral, derivative and manual output settings off. Enter a setpoint several degrees above the cooling systems lowest temperature. Enter a low proportional setting of approximately 5 or 10 and then enter the appropriate heater range as described above. The heater display should show a value greater than zero and less than 100%. The load temperature should stabilize at a temperature below the setpoint. If the load temperature and heater meter swing rapidly, the heater range may be set too high and should be reduced. Very slow changes in load temperature that could be described as drifting are an indication of a proportional setting that is too low (which is addressed in the next step).

Gradually increase the proportional setting by doubling it each time. At each new setting, allow time for the temperature of the load to stabilize. As the proportional setting is increased, there should be a setting in which the load temperature begins a sustained and predictable oscillation rising and falling in a consistent period of time. See Figure 2-3(a). The goal is to find the proportional value in which the oscillation begins, do not turn the setting so high that temperature and heater output changes become violent.

Record the proportional setting and the amount of time it takes for the load change from one temperature peak to the next. The time is called the oscillation period of the load. It helps describe the dominant time constant of the load which is used in setting integral. If all has gone well, the appropriate proportional setting is *one half* of the value required for sustained oscillation. See Figure 2-3(b).

Tuning Proportional (Continued)

If the load does not oscillate in a controlled manner, the heater range could be set too low. A constant heater reading of 100% on the display would be an indication of a low range setting. The heater range could also be too high, indicated by rapid changes in the load temperature or heater output with a proportional setting of less than 5. There are a few systems that will stabilize and not oscillate with a very high proportional setting and a proper heater range setting. For these systems, setting a proportional setting of one half of the highest setting is the best choice.

2.7.3 Tuning Integral

When the proportional setting is chosen and the integral is set to zero (off), the Model 331 controls the load temperature below the setpoint. Setting the integral allows the Model 331 control algorithm to gradually eliminate the difference in temperature by integrating the error over time. See Figure 2-3(d). An integral setting that is too low causes the load to take too long to reach the setpoint. An integral setting that is too high creates instability and cause the load temperature to oscillate.

Begin this part of the tuning process with the system controlling in proportional only mode. Use the oscillation period of the load that was measured above in seconds. *Divide 1000 by the period to get the integral setting.* Enter the integral setting into the Model 331 and watch the load temperature approach the setpoint. If the temperature does not stabilize and begins to oscillate around the setpoint, the integral setting is too high and should be reduced by one half. If the temperature is stable but never reaches the setpoint, the integral setting is too low and should be doubled.

To verify the integral setting make a few small (2 to 5 degree) changes in setpoint and watch the load temperature react. Trial and error can help improve the integral setting by optimizing for experimental needs. Faster integrals, for example, get to the setpoint more quickly at the expense of greater overshoot. In most systems, setpoint changes that raise the temperature act differently than changes that lower the temperature.

If it was not possible to measure the oscillation period of the load during proportional setting, start with an integral setting of 20. If the load becomes unstable reduce the setting by half. If the load is stable make a series of small, two to five degree, changes in the setpoint and watch the load react. Continue to increase the integral setting until the desired response is achieved.

2.7.4 Tuning Derivative

If an experiment requires frequent changes in setpoint or data taking between changes in the setpoint, derivative should be considered. See Figure 2-3(e). A derivative setting of zero, off, is recommended when the control system is seldom changed and data is taken when the load is at steady state.

The derivative setting is entered into the Model 331 as a percentage of the integral time constant. The setting range is 0 – 200% where 100% = ¼ I seconds. Start with a setting of 50 to 100%.

Again, do not be afraid to make some small setpoint changes; halving or doubling this setting to watch the affect. Expect positive setpoint changes to react differently from negative setpoint changes.

2.8 AUTOTUNING

Choosing appropriate PID control settings can be tedious. Systems can take several minutes to complete a setpoint change, making it difficult to watch the display for oscillation periods and signs of instability. With the AutoTune feature, the Model 331 automates the tuning process by measuring system characteristics and, along with some assumptions about typical cryogenic systems, computes setting values for P, I, and D. AutoTune works only with one control loop at a time and does not set the manual heater output or heater range. Setting an inappropriate heater range is potentially dangerous to some loads, so the Model 331 does not attempt to automate that step of the tuning process.

When the AutoTune mode is selected, the Model 331 evaluates the control loop similar to the manual tuning section described in Paragraph 2.7. One difference is that the Model 331 does not initiate changes to control settings or setpoint for the purpose of tuning. *It only gathers data and change control settings after the user changes the setpoint.* Unexpected or unwanted disturbances to the control system can ruin experimental data being taken by the user.

AutoTuning (Continued)

When the user selects a new setpoint, the Model 331 logs the change in temperature at the load and the change in heater output that was required to make the load temperature change. The old control settings are used while data is being logged, so a good initial guess of settings can improve the efficiency of the AutoTune feature. Once the load temperature is at or near the new setpoint, the Model 331 looks at the logged data to calculate the best P, I, and D settings values. Those values are then loaded and used as the control parameters so the control loop can stabilize at the new setpoint. AutoTune does not function during a ramp because the dominant time constant of the load is disguised by the ramp rate.

The **Tune** LED blinks to indicate that tuning data is being logged. The LED is illuminated but not blinking when the tuning process is complete. The LED will not blink again until the user changes the setpoint. If AutoTune does not give desired results the first time, make a few small (2 to 5 degree) changes in setpoint and let the Model 331 go until the **Tune** LED stops blinking. In many cases, AutoTune is able to arrive at a better set of control settings.

There are situations where AutoTune is not the answer. The algorithm can be fooled when cooling systems are very fast, very slow, have a large thermal lag, or are have a nonlinear relationship between heater power and load temperature. If a load can reach a new setpoint in under 10 seconds (with an appropriate I setting >500), the cooling system is too fast for AutoTuning. Systems with a very small thermal mass can be this fast. Adding mass is a solution, but is unappealing to users who need the speed for fast cycle times. Manual tuning is not difficult on these systems because new settings can be tested very quickly. Some systems are too slow for the AutoTune algorithm. Any system that takes more than 15 minutes to stabilize at a new setpoint is too slow (with an appropriate I setting <5).

Thermal lag can be improved by using the sensor and heater installation techniques discussed above. Lag times up to a few seconds should be expected, much larger lags can be a problem. System nonlinearity is a problem for both AutoTune and manual tuning. It is most commonly noticed when controlling near the maximum or minimum temperature of a temperature control system. It is not uncommon; however, for a user to buy a cryogenic cooling system specifically to operate near its minimum temperature. If this is the case, try to tune the system at 5 degrees above the minimum temperature and gradually reduce the setpoint, manually adjusting the control settings with each step. Any time the mechanical cooling action of a cryogenic refrigerator can be seen as periodic temperature fluctuations, the mass is too small or temperature too low to AutoTune.

2.9 ZONE TUNING

Once the PID tuning parameters have been chosen for a given setpoint the whole process may have to be done again for other setpoints significantly far away that have different tuning needs. Trying to remember when to use which set of tuning parameters can be frustrating. The Model 331 has a Zone feature as one of its tuning modes that can help.

To use the Zone feature the user must determine the best tuning parameters for each part of the temperature range of interest. The parameters are then entered into the Model 331 where up to ten zones can be defined with different P, I, D, heater range, and manual heater settings. A setpoint setting is assigned as the maximum temperature for that zone. The minimum temperature for a zone is the setpoint for the previous zone, 0 K is the starting point for the first zone. When the Zone tuning mode is on, each time the setpoint is changed to a new temperature, appropriate control parameters are chosen automatically.

Control parameters can be determined manually or by using the AutoTune feature. AutoTune is a good way to determined a set of tuning parameters for the control system that can then be entered as zones. Once the parameters are chosen, AutoTune is turned off and zone tuning takes over.

Zone tuning has advantages over AutoTune during normal operation. When a new setpoint is set the zone tuning automatically sets the appropriate control parameters for the destination. Approach to the new setpoint is controlled with the best parameters. AutoTune, on the other hand, is not able to learn enough about the system to change the control parameters until after the temperature gets near or to the new setpoint. Approach to the new setpoint is controlled with the old parameters because they are the best available.