Environmental Stress Systems, Inc.

PID Primer

What is PID?

PID stands for Proportional, Integral, and Derivative. The following explanations describe PID as it applies to the precise control of a **process** temperature. A **process** is an area or zone that is being controlled at or driven to a precise temperature. PID is a control method or mode that has three functions or variables. The *proportional* action dampens process response. The *integral* corrects for **droop**. **Droop** is the difference in temperature between the process **set point** and the actual process temperature. The **set point** is the desired process temperature. The *derivative* minimizes **overshoot** and **undershoot**. **Overshoot** is the amount in temperature units that the process temperature exceeds the set point before the **process stabilizes**. **Process stabilization** is achieved when the set point and process temperatures are equal over a defined period of time. **Undershoot** is the amount in temperature units that the process temperature falls below the set point before the process stabilizes.

Proportional is the **control output** effort in proportion to the error from set point. A **control output** is a signal action delivered in response to the difference between set point and process temperature. An output usually controls a heating or cooling action. The proportional range is referred to as a "band" and is usually measured in temperature units. If a **proportional band** of 20 degrees is applied to a process that is 10 degrees below set point, the heat output would be 50 percent. The lower the proportional band, the higher the **gain**. **Gain** is the amount of amplification used in an electrical circuit. Proportional band is sometimes referred to as gain. The **proportional band** or **PB** is a range in which the proportioning function of the controller is active. The PB units are usually expressed in degrees.

Integral is a control action that automatically eliminates droop or **offset**. **Offset** is the same as droop and is the difference in temperature between the process temperature and the set point. Droop or offset is a typical result when using proportional control. Integral is also known as "**Reset**".

Derivative is the rate of change in a process temperature. Large values prevent overshoot but can cause sluggishness. It is also known as "**Rate**".

What is Cascade?

Cascade as it applies to the precise control of a process temperature is a control algorithm in which the output of one **control loop** provides the set point for another loop. A **control loop** is a closed system comprised of four basic elements. A process to be controlled, a temperature sensor, a temperature controller, and energy source. The sensor measures the process temperature, compares it to the set point and drives an energy source to eliminate the **error**. The **error** is the difference between the set point and actual process temperature. The second control loop determines the **control action**. The **control action** is the response of the control output relative to the error between the process temperature and the set point.

Cascade is used to control a **difficult process** where minimal overshoot and quick stabilization are desired. A **difficult process** is described as a process in which there is long **thermal lag** or unacceptable **thermal gradients**. **Thermal lag** refers to the time it takes for the process sensor to measure the effect of an increase or decrease in the heating or cooling output. Long lag times can be caused by many conditions. Poor sensor location and or a thermally insulated sensor are two possible causes. A **thermal gradient** is the difference in temperature between the **device under test (DUT)** and the process at stabilization. A DUT with a large volume or mass, poor thermal conduction, or large and or varying heat dissipation can cause thermal gradients. These conditions would require cascade for precise control.

Thermal lag causes a lot of energy to be built up in the process before the sensor can detect a response. Delayed response results in overshoot and undershoot or **oscillations**. **Oscillations** as applied to process control refer to a state where temperature overshoot and undershoot continue to occur over a long period of time without diminishing. In other words, the error between set point and process temperature cannot be eliminated and stabilization never occurs.

A process with long lag times or thermal gradients cannot be controlled precisely with a single loop controller because energy would build up and cause thermal oscillations. It may be possible to reduce the oscillations by using PID settings that minimize overshoot but the time it would take for the process to reach set point and stabilize would be unacceptably long.

Cascade utilizes two loops to provide precise control in a long lag time process. The two loops are described as the inner loop and the outer loop. Each loop has a thermal sensor. The sensor on the inner loop is located in close proximity to the **energy source**. An **energy source** is typically a heater or coolant supply. The sensor on the outer loop is located in close proximity to the DUT. The inner loop (energy) sensor is used to prevent the excessive build up of energy. The outer loop (DUT) sensor is used to provide precise temperature control of the DUT. Cascade software in the controller is used to drive the energy output based on the input from the two sensors.

Cascade requires that a **temperature range** be set for the energy source. A **temperature range** is the amount in degrees that the inner loop temperature (energy source) can exceed the set point in an effort to bring the DUT to the set point with minimal overshoot and the shortest stabilization time. The range is a relative value based on the current set point. There is a high setting for the heat energy source and a low setting for the cooling source. The range high setting is a positive number and the range low setting is a negative number. The range high and low settings are usually based on the maximum temperature gradient that you want to eliminate that occurs between the DUT and process when stabilization first occurs. For example, if a set point of 100 is selected, there may be a difference of several degrees between the DUT temperature and the process temperature. The range setting allows the process to heat up beyond the set point to drive the device to 100 degrees.

The inner and outer loop each have their own set of PID variables to provide precise control. Each loop must have the correct PID values in order for the cascade to function properly. The inner loop (energy source) is assigned PID set B (PIDB) and the outer loop (DUT) is assigned PID set A (PIDA). The inner loop PIDB set is **tuned** first. **Tuning** is the process of entering PID variables and watching the effect on the process until satisfactory control and stabilization result. Once the inner loop PIDB is set properly, then the outer loop PIDA set must be tuned.

Tuning the PID Values for Normal Control

Normal control refers to single loop control. Another section will cover tuning PID values for cascade control. PID values are set at the factory and under normal conditions should not need to be changed. However, if you determine that your process requires adjustment of the PID values, or you are using cascade control, you may need to enter new PID values. There are many good reference books available on PID. This section is not meant to be an in depth study of PID but simply to provide a basic “hands on” technique for PID tuning. There are other viable methods of determining good PID settings but the following method is one that has worked well for us.

Warning! Improperly set PID values can cause erratic process control. Do not attempt to change the PID values unless you have read and understand the following sections.

The effect of changed PID values on a process is best observed when a large change in process temperature occurs. For example, if you typically test at 85 degrees then a good test of PID values would be to observe their effect on overshoot, undershoot and stabilization time on a process that begins at 25 degrees and ends at 85 degrees. The greater the temperature change the more accurate the evaluation of the PID values will be.

Proper PID tuning starts by recording the current PID values for Proportional, Reset and Rate and then setting the three PID variables Proportional, Reset and Rate to a value of zero (0).

There are a couple of other system values that need mentioning although they are not a part of the PID tuning procedure. When setting up a process there are some other terms that you should be aware of. **Dead Band** or **DB** refers to the temperature band around the set point that determines when the output will shut off. DB is only used in **ON/OFF control**. **ON/OFF control** describes a process that does not use proportional control such as a home heating and air conditioning system. If PB is set to zero (0) then a value other than zero (0) must be entered for DB. Without a DB, an ON/OFF process could rapid cycle as soon as it hit set point. Since all of our systems utilize proportional control, the DB value is not important and should be set to zero (0).

Hysteresis is the amount of change in the process temperature that is required to re-energize the control output after it has shut off. This is the temperature in an ON/OFF process where the output will turn back on again after it has turned off. For example, in an ON/OFF process when in cooling mode, with a dead band of –1.0 degrees and a hysteresis of +2.0 degrees you would have the following action:

If the process is at 80 degrees and you enter a new set point for 70 degrees, the cooling output would turn on until the process reaches 69 (DB of –1.0 degrees) and then it would turn off. The cooling output would not turn on again until the process temperature reaches 71 degrees (hysteresis of +2.0 degrees. Note that the hysteresis is measured from the dead band turn off point and not from the set point. As with dead band, hysteresis is only a factor when in an ON/OFF control mode. In proportional mode (a PB greater than zero) hysteresis can be set to zero (0).

Cycle time is the time required for the controller to complete one on-off-on cycle (do not confuse with ON/OFF control). Cycle time is the period of time that the process controller can make an adjustment to the output **duty cycle** based on the error between set point and process temperature. **Duty cycle** is the amount of time that the output remains energized during the cycle time period. What this means is that the controller will break up the job of controlling the process temperature into little windows of time. The duration of each time period is determined by the cycle time value. Proportional control is often based on time and is therefore also referred to as **time proportioning** control. This is how it works:

If you have a cycle time of 5 seconds and the PID control calls for an output duty cycle of 50% then the output will be on for 2-1/2 seconds and off for 2-1/2 seconds. The duty cycle “on time” plus the “off time” will equal the cycle time period. Likewise if the output duty cycle is 20% then there would be a 1-second on time with a 4 second off time. The controller is constantly monitoring the error and will adjust the output duty cycle as necessary for each cycle time period. The shorter the cycle time the more precise the control. However, very short cycle times can cause electromechanical devices to wear out prematurely. A good rule of thumb is to use a minimum of a 5-second cycle time for any output that utilizes an electromechanical device such as a solenoid valve. Devices such as resistive elements (heaters) can use as short a cycle time as desired because there are no moving parts to wear. Cycle time for non-electromechanical devices can be 1 second or less.

Burst or zero cross firing is term used to describe a type of control method that can yield more precise control and longer energy source life. It can only be used with devices that have no moving parts such as heater elements. **Burst firing** repeatedly turns on and off full AC cycles. It is also called **zero cross firing** because it switches close to the zero voltage point of the AC sine wave. Burst firing selectively holds or transits AC cycles to achieve the desire output power level. Burst firing offers a much more precise method of control with a maximum of a 1.66-second time base to a minimum 33.3 millisecond time base. Element life is also prolonged.
In a typical heat cool system, there is a separate set of PID values for the heat output and the cool output. Output # 1 is typically the heat output and output # 2 is typically the cool output. PB1 would be the proportional band for output # 1 and PB2 would be the proportional band for output # 2. In cascade control where you have two sets of PID values for each output you would have PB1A and PB1B. PB1A is proportional band output # 1 set A. PB1B would be proportional band output # 1 set B. A chart later in this section will show all of the abbreviations with their explanations.

Tuning PID variables always starts with setting the proportional band for the output you are tuning with the Reset and Rate values set to 0. Since the different PID values are related, it is best to work with one value at a time. Once one value has been set properly, the next value can be adjusted, observing the effect it has on the process. If you are tuning the heat output then you will be setting proportional band # 1 first. Start with the process at room temperature. Enter a starting PB value of 10 and enter a set point of the highest temperature your process will typically be run at such as 100 degrees. Watch the process heat up and observe the overshoot, undershoot, and if the oscillations decrease over time or stay the same. It will be necessary to cool the process back down to room temperature when you change the PB value and to send the process back to 100 degrees to accurately observe the effect of the change on the process. Study the charts below and adjust the PB value as necessary to get the desired results.

Note: A strip chart recorder or other data recorder such as a data logger is very helpful in determining the effect that a change in a PID setting has on the overall process. In the absence of automated data recording equipment, a watch with a second counter and a pad of notepaper can be used. Record temperatures in as short of intervals as is practical for the most accurate results. You can create your own charts similar to the ones at the end of the section using a “connect the dot” technique.

Once the PB value has been set correctly you should have minimal overshoot, minimal droop and minimal oscillations. Proceed to setting the Reset (Integral) value. Carefully increase the Reset value until the droop is eliminated. A good starting point would be a value of about 0.20. A Reset setting that is too high will re-introduce oscillations into the process. A Reset value that is to low will either not eliminate the droop or eliminate it over a very long period of time.

Once the Reset has been set correctly, you should observe a single minimal overshoot, followed by a single minimal undershoot, with a droop that is eliminated in a short period of time, followed by a stable process temperature with very little error. At this point you can proceed to setting the Rate (Derivative) value. The Rate or Derivative value can have a large and undesirable effect on the process if it is set too high. Very carefully increase the Rate value to eliminate the initial minimal overshoot and undershoot. If at any time oscillations are re-introduced into the process then reduce the Rate value. A good starting Rate value would be 0.05. In some cases it is best to leave the Rate value set to 0. If after setting the PB and Reset correctly you observe oscillations when a Rate value is added, return the Rate value to 0.

As a general rule, any time there are unacceptable oscillations observed in a process, then one of the PID values is set incorrectly. The advantage of setting one value at a time in the exact order outlined above is that it is easy to identify which PID value is introducing the undesirable oscillations and to make the necessary adjustment.

Once the PID values have been correctly set for output # 1, proceed to set the output # 2 values in the same manner as outlined above. Keep in mind that the graphs provided would be inverted when you are tuning for process temperatures below ambient.

PID abbreviations table

PB1A	Output 1 proportional band set A
RE1A	Output 1 reset set A
RA1A	Output 1 rate set A
CT1A	Output 1 cycle time set A
PB2A	Output 2 proportional band set A
RE2A	Output 2 reset set A
RA2A	Output 2 rate set A
CT2A	Output 2 cycle time set A
DBA	Dead band set A

PB1B	Output 1 proportional band set B
RE1B	Output 1 reset set B
RA1B	Output 1 rate set B
CT1B	Output 1 cycle time set B
PB2B	Output 2 proportional band set B
RE2B	Output 2 reset set B
RA2B	Output 2 rate set B
CT2B	Output 2 cycle time set B
DBB	Dead band set B

Tuning the PID Values for Cascade Control

Tuning the PID values for cascade control mode is similar to normal control tuning. The main difference is that there are two sets of PID values corresponding to the two sensor feedback loops. The order is also critical. In cascade mode you always tune the B set of PID values first. The B set of PID values is assigned to the inner loop (energy source). After the B set is tuned, proceed to the A set. The A set is assigned to the outer loop (DUT). The B set has a discreet set of values for output 1 and output 2 respectively. The A set has a single set of PID values.

Cascade control enables a difficult process to be controlled with minimal overshoot and rapid stabilization. A long lag time process cannot be precisely controlled with a single loop approach because a lot of energy can build up before a response can be detected by the process sensor. Built up energy causes overshoot and oscillations.

Be aware that the Rate variable for set A (outer loop) (RA1A) can introduce instability into the process even more so that usual. Use a value of zero (0) if possible.

Using the charts provided, tune the PID B set to achieve stable control as outlined in the charts. Once stable control of the energy source is achieved tune the PID A set to get good control at the device.

Cascade control checklist:

- Be sure that the sensor # 1 and sensor # 2 are connected to the proper location on the process. In normal control, sensor # 1 is attached to the energy source and sensor # 2 is attached to the DUT. In normal control, sensor # 2 acts only as a monitoring sensor to indicate DUT temperature. It is not a part of the control loop. In cascade control, sensor # 1 is attached to the DUT and sensor # 2 is attached to the energy source. Both sensors are critical components of the control loop. Failure to connect the sensors properly will result in erratic control.

- Be sure that sensor # 1 is securely attached to the DUT in a location that best matches the desired temperature monitoring point as outlined in the test procedures.

- Be sure that sensor # 2 is connected to the energy source.

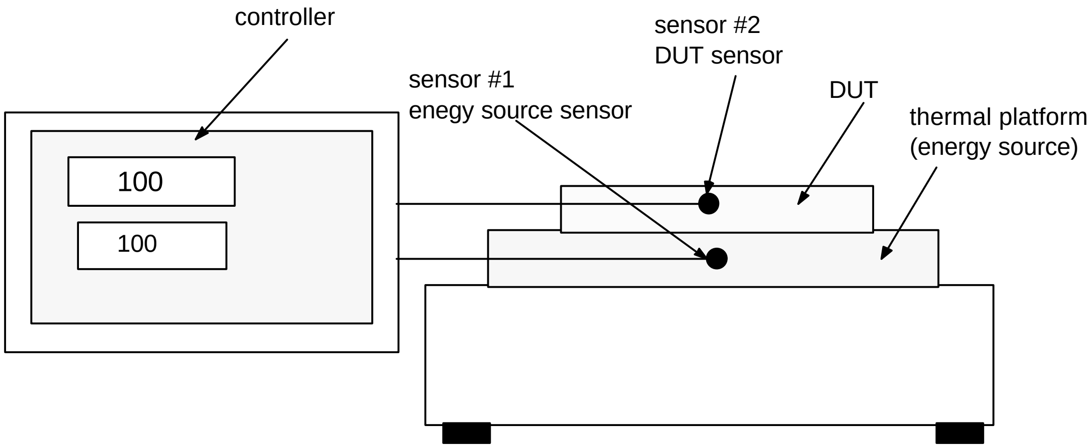
- Set up the RC900 for “cascade” under “control type” and “direct” under “cascade action” in the Global menu. See RC900 operation manual.

- Set the high and low range values for input # 2 (RL2 and RH2) in the Input menu. Factory default is –10 for RL2 and +10 for RH2.

- Tune inner loop (energy source) PID set B values.

- Tune the outer loop (DUT) PID set A values.

Typical normal control application. DUT is low profile and responds quickly to changes in thermal platform temperature



Typical cascade control application. DUT is high profile and responds slowly to changes in thermal platform temperature. Normal control would allow unacceptable thermal gradients. Moving single loop sensor to DUT would allow energy build up that would result in oscillations and instability.

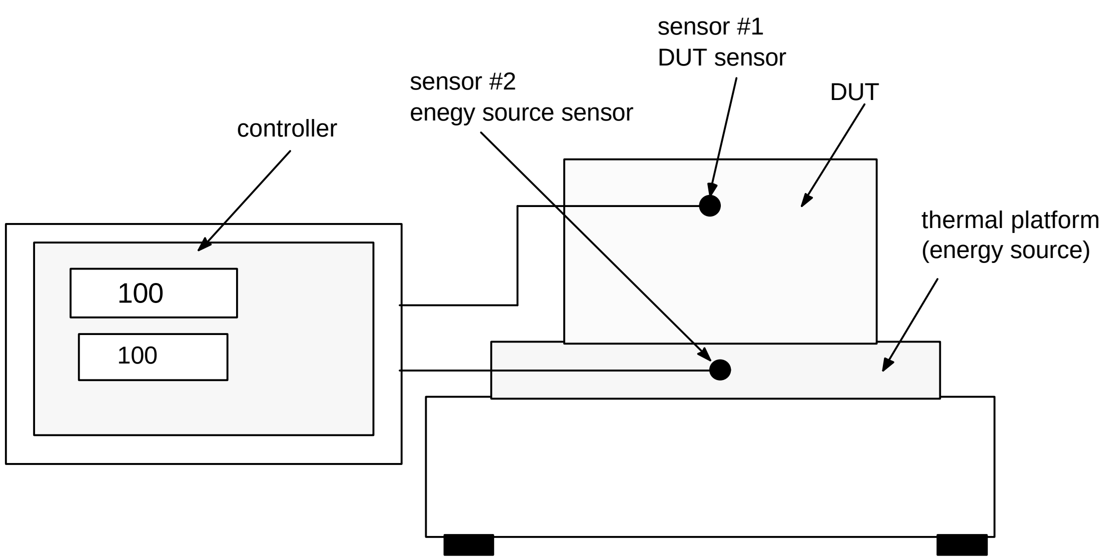


Table 1

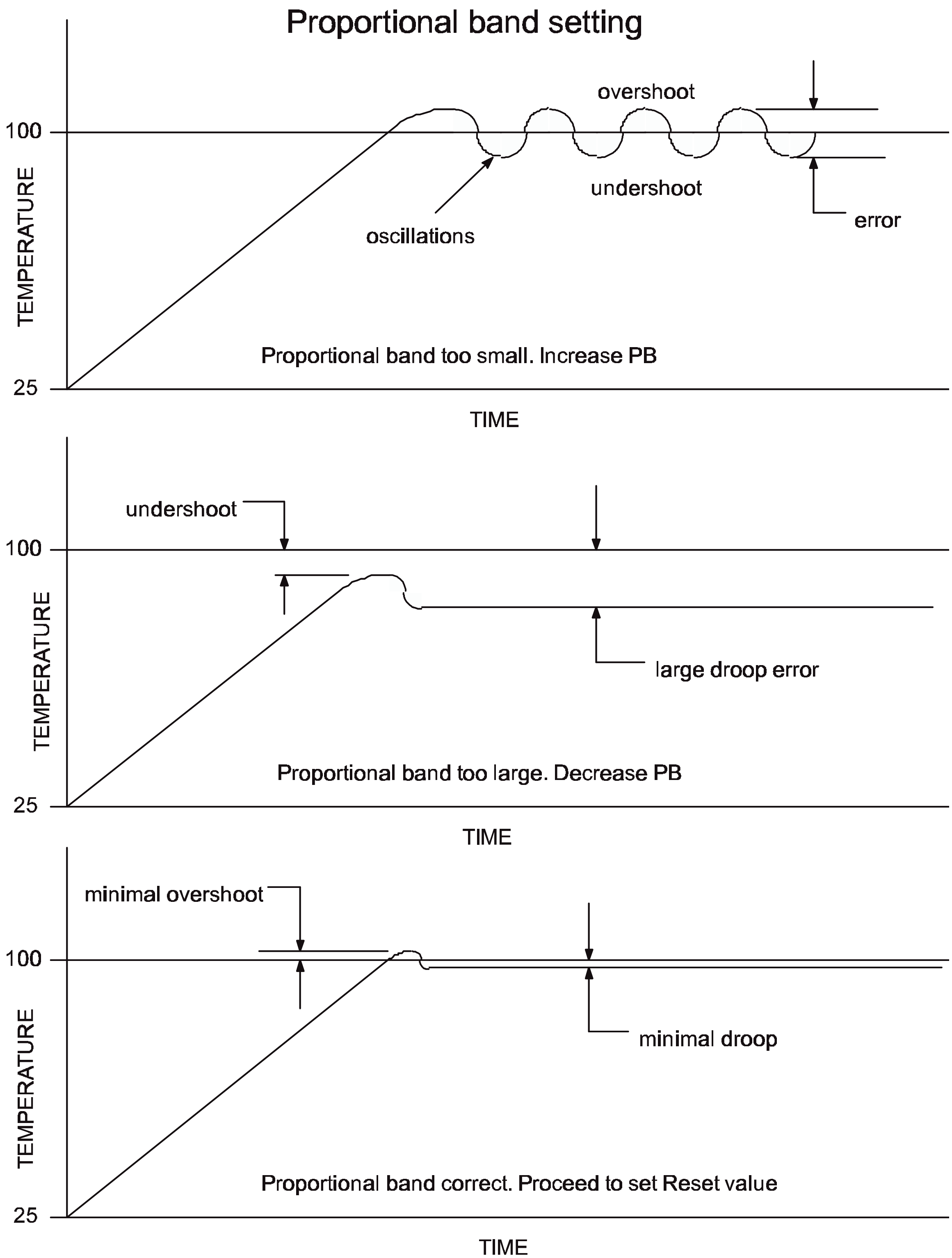

Proportional band setting
overshoot
100
undershoot
error
oscillations
TEMPERATURE
Proportional band too small. Increase PB
25
TIME
undershoot
100
large droop error
TEMPERATURE
Proportional band too large. Decrease PB
25
TIME
minimal overshoot
100
minimal droop
TEMPERATURE
Proportional band correct. Proceed to set Reset value
25
TIME

Table 2

Reset (Integral) setting

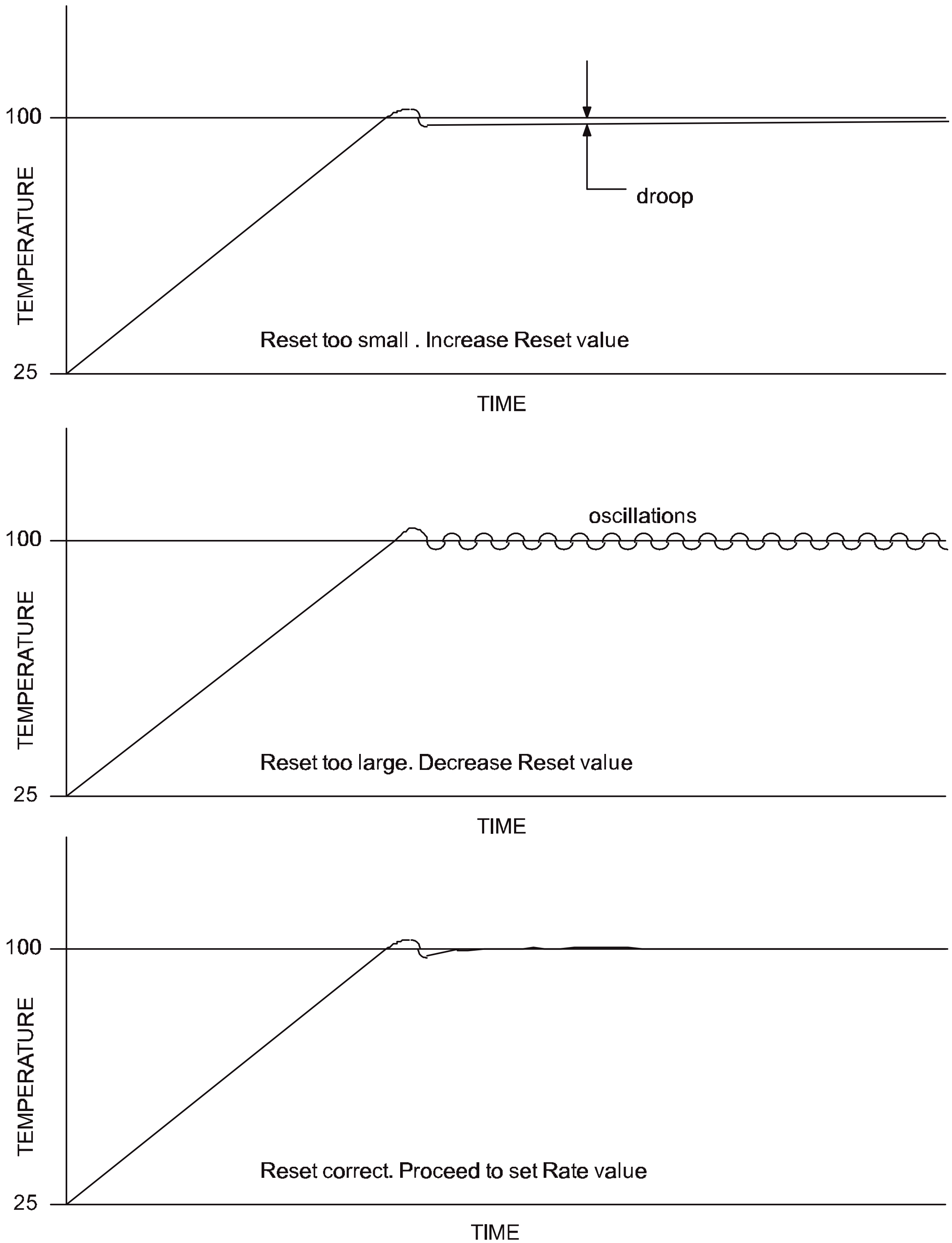
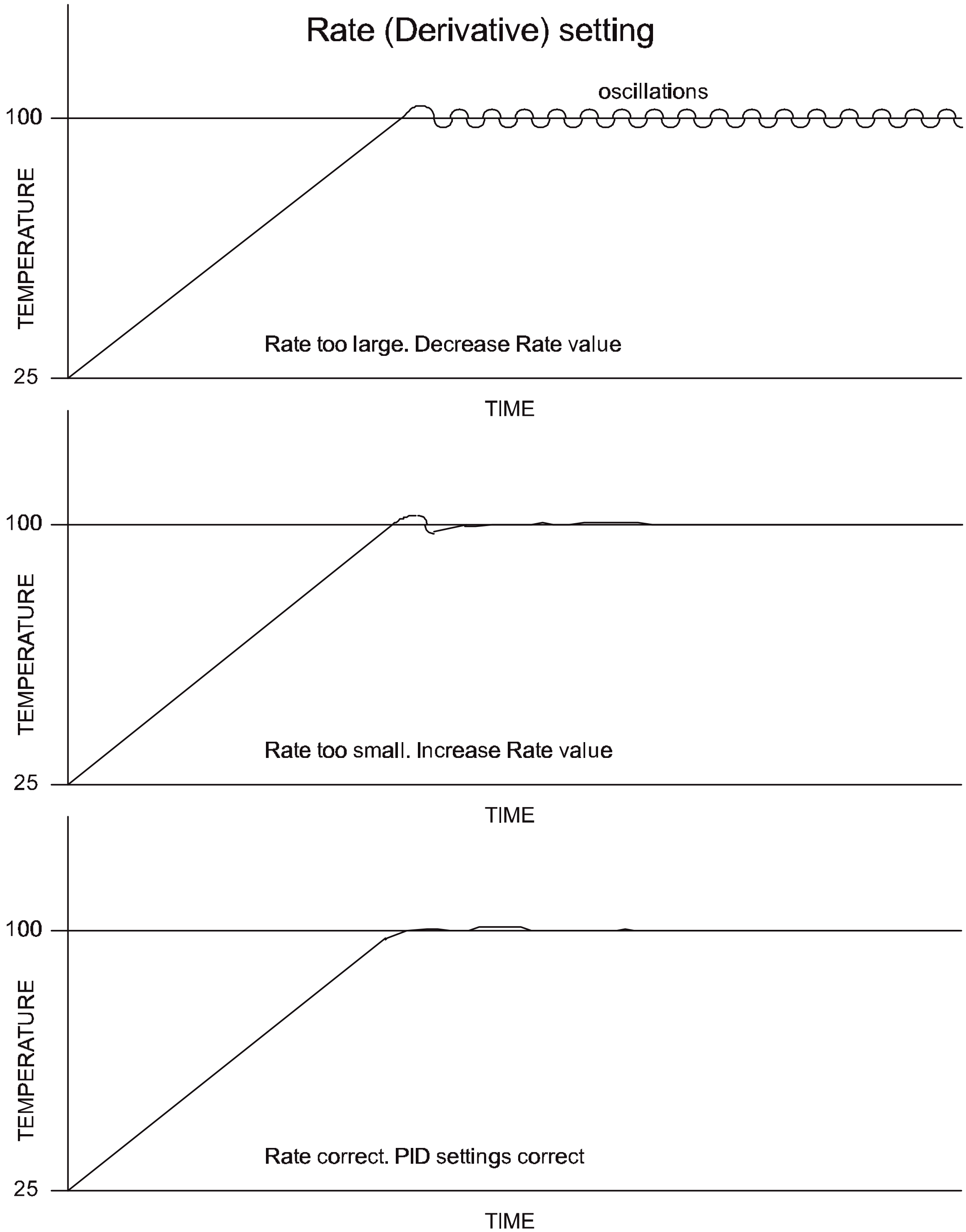


Table 3



Rate (Derivative) setting
oscillations
100
TEMPERATURE
25
Rate too large. Decrease Rate value
TIME
100
TEMPERATURE
25
Rate too small. Increase Rate value
TIME
100
TEMPERATURE
25
Rate correct. PID settings correct
TIME