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Ron Beaufort Training, LLC
5900 Core Avenue, #102
Charleston, SC 29406
843-437-1883   www.ronbeaufort.com

Hands-On Technical Workshops
by Ron Beaufort

Sample Lessons and Knowledgebase

What is P in PID? ... a (too) simple answer: it is the "Proportional" component of Proportional-Integral-Derivative control ...

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foreword by Ron Beaufort: I have previously posted much of the material contained in this paper on the "Live Question and Answer" forum at www.PLCs.net ... this was just one in a series of related threads which discussed the basic characteristics of the three components of PID control ... anyone who is interested in following the full context of the questions and answers of the original threads should be able to find them at the following links:

What Is P in PID? http://www.plctalk.net/qanda/showthread.php?t=13459
What Is I in PID? http://www.plctalk.net/qanda/showthread.php?t=11242
What Is D in PID? http://www.plctalk.net/qanda/showthread.php?t=11969
Proportional-only Control – Why Won't It Work?
          http://www.plctalk.net/qanda/showthread.php?t=14497

since my original postings, many readers have requested that I make the text and illustrations easier to access by providing a single continuous PDF file of the material ... this document is the result of those requests ... I've reformatted some parts of the text and added more detail in certain places to make the ideas easier to follow ... most of the forum's original conversational tone has been left in place ...

while I believe that the information included here is correct, it is offered free of charge with no warranty of any kind ... it may be copied and distributed as long as there is no commercial interest involved and as long as the material is copied and transferred in its entirety - including this notice and all notices of copyright ...

I hope that this material proves helpful ... corrections, comments, and suggestions from readers are always welcome ...

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well, you've got to start somewhere ... so this paper assumes (rightly or wrongly) that the reader is already familiar with the very basic idea that PID (Proportional-Integral-Derivative) is a mathematical function (an equation) which may be used to automatically control systems such as temperatures, flow rates, speeds, pressures, levels, etc. ... the subject of this paper is the Integral component of PID control as used in many different types of Allen-Bradley PLCs (Programmable Logic Controllers) ... please keep in mind while reading this that there are exceptions to every rule ... this material is intended to be a beginner's level introduction to a very complex subject ... in order to keep things as straightforward as possible, it has been necessary to leave out quite a few topics which I wish I had time and space to cover ... but this is at least a starting point at answering the basic question:

What is P in PID?

I've had some pretty good success using the following explanation in the hands-on "technician level" PID classes that I teach ... most of the students in those classes need to work around PID-controlled systems, but they don't really have very strong math skills ... anyway ... let's see if this approach helps you too ...

first things first ... there are MANY different ways of setting up PID
control ... but so that we'll have a specific brand and model of
controller for our examples, I'll be using the Allen-Bradley PID for this
discussion ... specifically, I'll be using the "Dependent Gains" equation
(or as it's also known) the "ISA" equation of a PLC-5 processor ...

note: in addition to the most-common "Dependent Gains/ISA" equation, the
PLC-5 and ControlLogix platforms also support the "Independent Gains" or
(as it's also known) the "AB" equation ... fortunately for the topic of
this discussion, both of these equations perform the Proportional action
in exactly the same manner ... so as far as the Proportional action is
concerned, the biggest differences between the various Allen-Bradley
platforms are in the ranges of the analog input and output signals used by
each controller ... where possible, I'll use "percentages" for these units
rather than the raw data values ... students using the SLC-500 and
MicroLogix controller platforms should be able to follow the basic ideas
of this text by mathematically converting between the different data
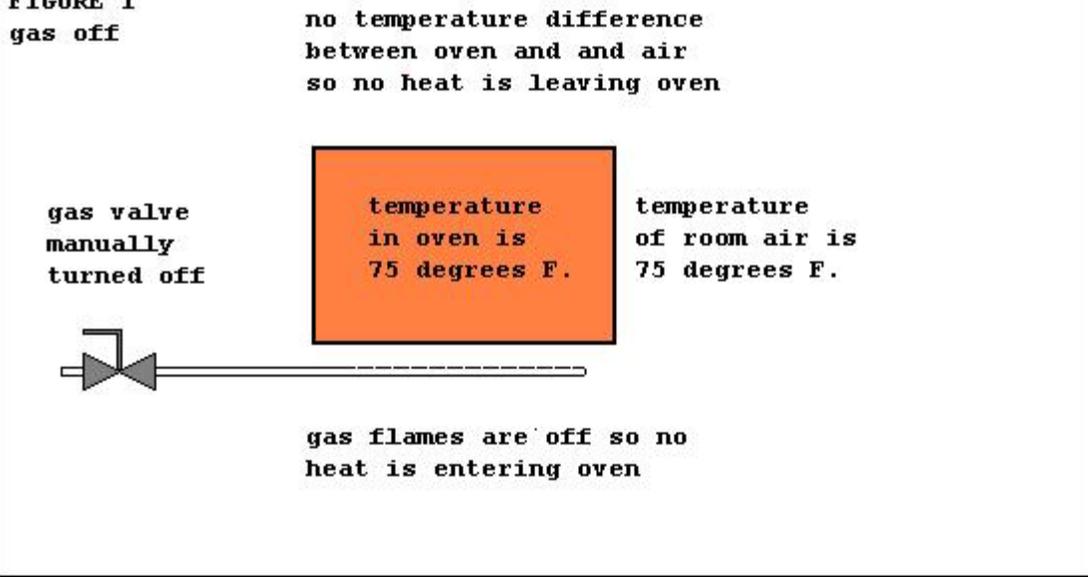ranges involved ...

and so for the basic question: "What is P in PID?" ... one simple answer
is that "P" represents the Proportional action ... and that it reacts to
the amount of Error – the difference between the SP (Setpoint) and the PV
(Process Variable) ...

well, if you're anything like I am, answers like that one leave much to be
desired ... they seem to be written by people who fully understand the
subject – and intended for other people who already fully understand the
subject ... that doesn't help me out a great deal ... and so the material
that I'm posting here is intended for people who do NOT already understand
the subject ...

going one step further, as everyone is certainly aware, all students are
not "created equal" ... the same explanations that can be effectively to
teach one, might not work at all while trying to teach another ...
throughout this thread I'll be using some of the most effective methods of
explaining the topic that I've used over the years in my week-long PID
classes ... keep in mind that these classes are not intended for engineers
who will be setting up a control strategy for a new system – but rather
for maintenance technicians who will be working on and around existing
systems ... and specifically on Allen-Bradley PLC systems ... basically
that means that the "elegant" math (calculus, differential equations,
etc.) that most people expect (and many people dread) will not be included
here ... instead I've always had good success from using a more "common
sense" approach to explain the ideas involved ... and I promise that the
math included here will never get any more complicated than the simple
arithmetic used to balance a checkbook or calculate a proper tip for a
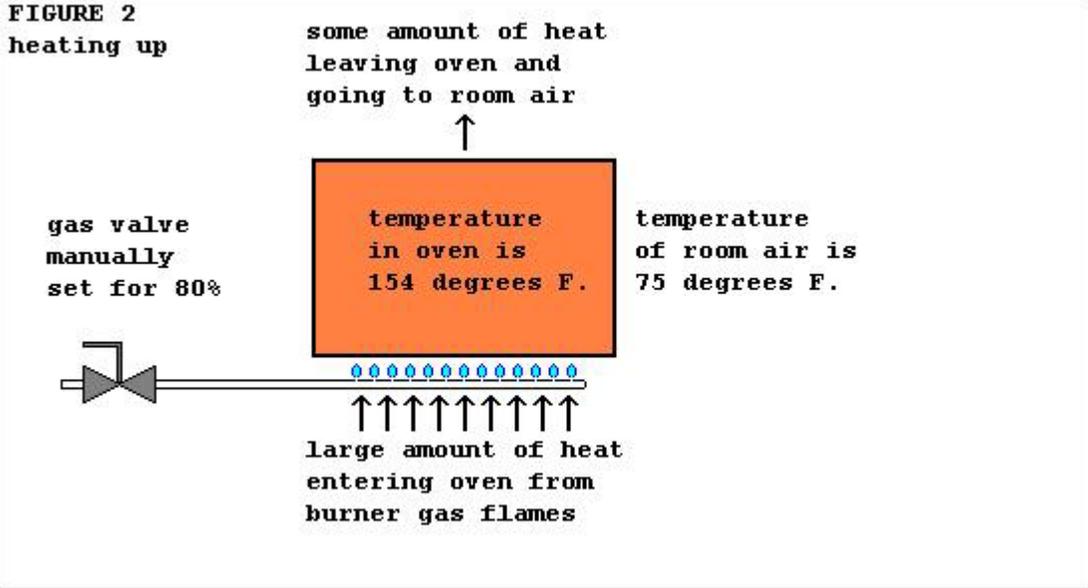good waiter ...

moving right along ... before we can really understand how the PID's
Proportional action functions, we need to have a basic idea of how a
typical process reacts when placed under any type of automatic control ...
we'll use a simple gas oven as an example ...

```
FIGURE 1
gas off                   no temperature difference
                          between oven and and air
                          so no heat is leaving oven


gas valve             temperature        temperature
manually              in oven is         of room air is
turned off            75 degrees F.      75 degrees F.




                      gas flames are off so no
                      heat is entering oven
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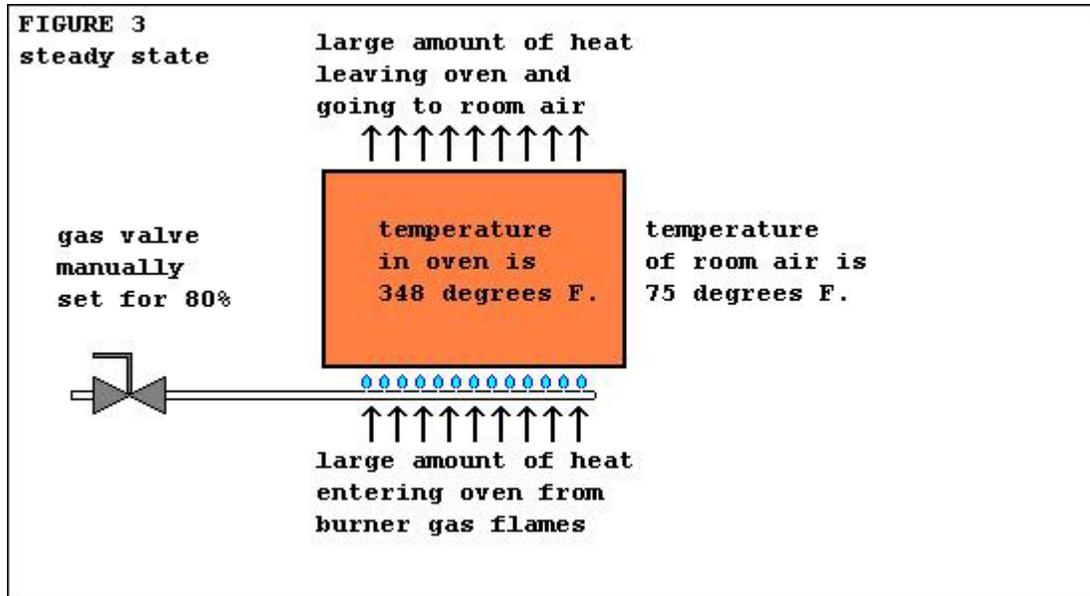
in Figure 1 the gas to the oven has been turned off for a very long time
... the temperature of the room air surrounding the oven is 75 degrees F
... the oven has cooled down so that its temperature is also exactly 75
degrees ... in other words, the system has reached a "steady state" in
which it will neither heat up, nor cool down, until something is changed
... as noted in the figure, there is no heat entering the oven ... and no
heat leaving the oven ...

```
FIGURE 2             some amount of heat
heating up           leaving oven and
                     going to room air
                            ↑

gas valve             temperature        temperature
manually              in oven is         of room air is
set for 80%           154 degrees F.     75 degrees F.


                     ↑↑↑↑↑↑↑↑↑
                     large amount of heat
                     entering oven from
                     burner gas flames
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in Figure 2 the gas valve has been manually set for 80% of full flow ... a
large amount of heat from the burner is now entering the oven ... as the
oven heats up from its initial 75 degrees condition, a difference of
temperature develops between the oven and the surrounding room air ... the
laws of physics say that this condition will cause heat energy to leave
the hotter oven and flow into the cooler room air ... and (this is the
important part) the GREATER THE DIFFERENCE between the temperature of the
oven and the temperature of the air, then the GREATER THE AMOUNT of heat
which will flow ... let's suppose that the temperature of the oven has

increased to 154 degrees as shown in the figure ... the room air is still
at 75 degrees ... and so "some" amount of heat is now leaving the oven ...
of course the amount of heat coming from the gas burner is very large ...
and so despite the loss of heat to the surrounding air, the oven continues
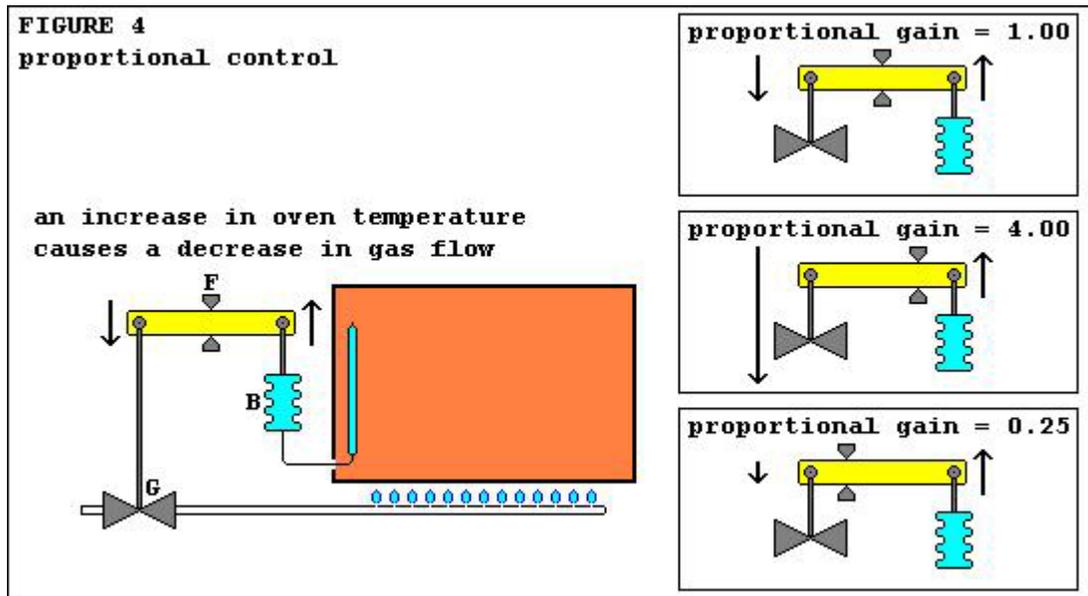to get hotter ... and hotter ...

FIGURE 3
steady state

large amount of heat
leaving oven and
going to room air

temperature
in oven is
348 degrees F.

temperature
of room air is
75 degrees F.

gas valve
manually
set for 80%

large amount of heat
entering oven from
burner gas flames

in Figure 3 our system has reached another "steady state" ... the
temperature of the oven has increased to 348 degrees ... the room air is
still at its original 75 degrees ... and even though the gas burner is
still turned on to its 80% setting, the oven will NOT increase in
temperature ... that's because the increased difference in temperature
between the hot oven and the cool air is now sucking heat OUT OF the oven
EXACTLY as fast as the gas flame can push heat INTO the oven ...

it is VERY important that you understand this concept ... let's nail it
down ... while we're trying to heat our oven, it's as though there is an
invisible "LOAD" which is working against us ... and the most important
thing about this load is that it does NOT remain constant ... instead it
increases in strength as the difference in temperature between the oven
and the air increases ... if it were not for this increasing load on our
system, then the oven temperature would continue to climb – and climb –
and climb ... and eventually we'd have a melt-down condition ... the only
reason that this doesn't happen is because - at some definite point - the
amount of heat leaving the oven eventually BALANCES the amount of heat
entering the oven ... it EXACTLY balances ... and that's what causes the
steady state condition that we see in Figure 3 ...

consider what would happen if the room temperature were to increase to 80
degrees ... in that case the temperature difference between the oven and
the air would DECREASE ... and so less heat would flow from the oven to
the air ... and the temperature of the oven would increase above the
steady state condition of 348 degrees shown in our example ... and
eventually some new steady state temperature would result ... let's assume
for a moment that the previous 348 degree oven temperature was "just
right" ... to maintain our "just right" temperature of 348 degrees under
these new "hotter room air" conditions, we'd have to manually change our
gas valve setting in order to decrease the amount of heat supplied to the
oven ...

and of course if the room temperature were to decrease to 70 degrees, then the temperature difference between the oven and the air would INCREASE ... and so more heat would flow from the oven to the air ... and the temperature of the oven would decrease below the steady state condition of 348 degrees shown in our example ... eventually some new steady state temperature would result ... under these new "cooler room air" conditions, we'd have to manually change our gas valve setting to increase the amount of heat supplied to the oven in order to maintain our "just right" temperature of 348 degrees ...

FIGURE 4
proportional control

an increase in oven temperature causes a decrease in gas flow

proportional gain = 1.00

proportional gain = 4.00

proportional gain = 0.25

in Figure 4 we've improved our oven to include automatic control for the gas valve ... specifically, we've added "Proportional" control ... item B is often referred to as a "bellows motor" ... basically it's a small metal container connected to a sensor bulb by a very thin hollow tube ... when the fluid inside the bulb (something such as mercury) is heated, it expands ... this increases the pressure inside the bellows motor ... the corrugated design of the bellows allows it to also expand ... this provides a linear motion which raises the right end of the lever ... the lever pivots at the fulcrum F so that as the right end rises, the left end lowers ... this action slightly closes the gas valve G ... and the higher the oven temperature, the more the gas valve closes ...

soon we'll replace this mechanical controller with a PLC-based PID instruction ... but in the meantime, we can learn a lot about how the Proportional adjustment functions by studying the lever action shown in the three detail sketches of Figure 4 ...

consider the word "proportion" ... another word that could be used for this type of action is "ratio" ... and one very common example of a "ratio-in-action" is a simple lever ...

in the top detail, the fulcrum point is positioned exactly at the center of the lever ... this adjustment sets up a "one-to-one" ratio between the amount of movement at the bellows end of the lever and the gas valve end ... in technical terms, this adjustment could be referred to as a setting for a Proportional gain of 1.00 ...

in the middle detail, the fulcrum has been repositioned closer to the right end of the lever ... let's assume that the "bellows end" of the

lever is now just one-fourth as long as the "gas valve end" ... this
adjustment sets up a "one-to-four" ratio between the amount of movement at
the bellows end of the lever compared to the gas valve end ...
specifically, now any amount of movement from the bellows will move the
gas valve four times as far ... this adjustment could be referred to as a
setting for a Proportional gain of 4.00 ...

in the bottom detail, the fulcrum has been repositioned closer to the left
end of the lever ... let's assume that the "bellows end" of the lever is
now four times as long as the "gas valve end" ... this adjustment sets up
a "four-to-one" ratio between the amount of movement at the bellows end of
the lever compared to the gas valve end ... specifically, now any amount
of movement from the bellows will move the gas valve only one-fourth as
far ... this adjustment could be referred to as a setting for a
Proportional gain of 0.25 ...

while this type of mechanical linkage might look crude and old-fashioned,
you should keep in mind that there are still many systems in use today
that rely on these same concepts ... more importantly, the Proportional
action of our modern PLC-based control is directly descended from the
methods shown in Figure 4 ... and so as you type in various numbers to
"tune" the PID's Proportional action, it might help to think about how
this type of control was originally adjusted by mechanically shifting the
fulcrum point of a simple lever ...


FIGURE 5   ON/OFF CONTROL
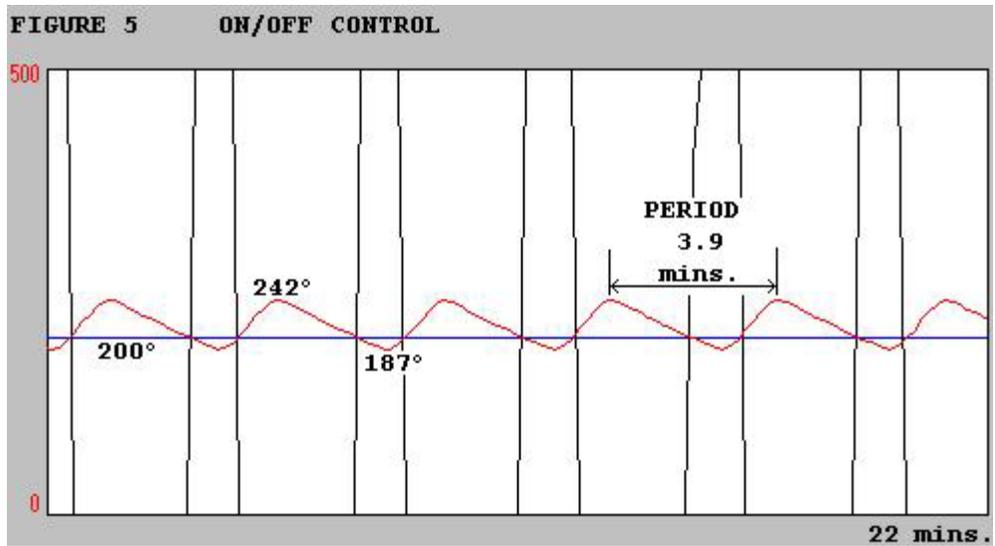
in Figure 5 we've set up a PLC-5 to control the Hotrod trainer which I use
for student lab exercises ... well, actually it's the "Ramrod" which is a
software simulated Hotrod ... but, for our purposes today, the operation
will be identical to the real thing ...

before we dig into PID control, it might be a good idea to take a quick
look at the On/Off control being used in Figure 5 ... notice that the
Ramrod has been adjusted for a Setpoint of 200 degrees ... incidentally,
we'll keep this same Setpoint throughout all of the examples in this
discussion ... the data shown in Figure 5 was captured after the system
had been in operation for quite awhile ... notice that the temperature is
continuously oscillating between a maximum of 242 degrees and a minimum of
187 degrees ... another thing to notice is that the Ramrod system heats up
faster than it cools off ... you can tell this because the "heating up"
side of each wave has a greater angle to its slope than the angle of the
"cooling off" side of the wave ... notice also that the Ramrod's natural

period of oscillation is approximately 3.9 minutes ... that gives us about
five and a half waves during our 22 minute graph ...

now honestly none of these features are critical to our discussion of
Proportional control ... but Figures 5 and 6 (which follows) might help a
more experienced reader get a "feel" for the Ramrod's operating
characteristics ...
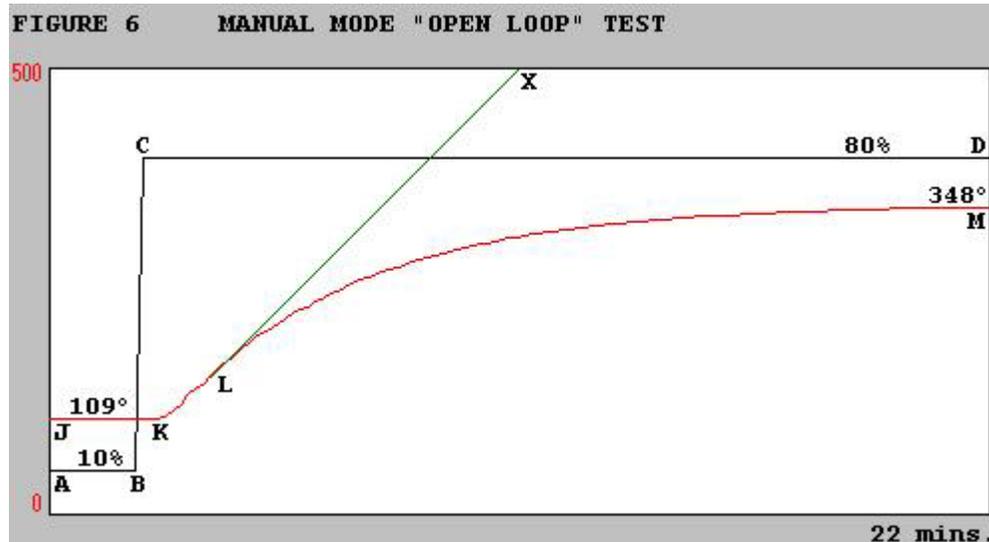
in Figure 6 we have an "open loop" test which was run in the manual mode
... like the test shown in Figure 5, this one is also intended to
demonstrate some of the operating characteristics of the Ramrod ... we
need to spend some time on this one ...

before we get started, be sure that you realize that the Setpoint is NOT
shown on this graph ... that's because for this particular test we're
operating in the manual mode ... the black trace shown by points A, B, C,
and D is the CV (Control Variable) ... it shows how much "drive" is being
fed to the heater ... the fact that the PV does not "follow" the black
trace is of absolutely NO importance ... do not get caught up in this
common beginner's mistake ...

now notice that the CV started out at point A and was kept at a constant
10% setting up to point B ... then at point B the CV was suddenly
"stepped" from its 10% setting all the way up to an 80% setting at point C
... then it was kept steady throughout the rest of the graph all the way
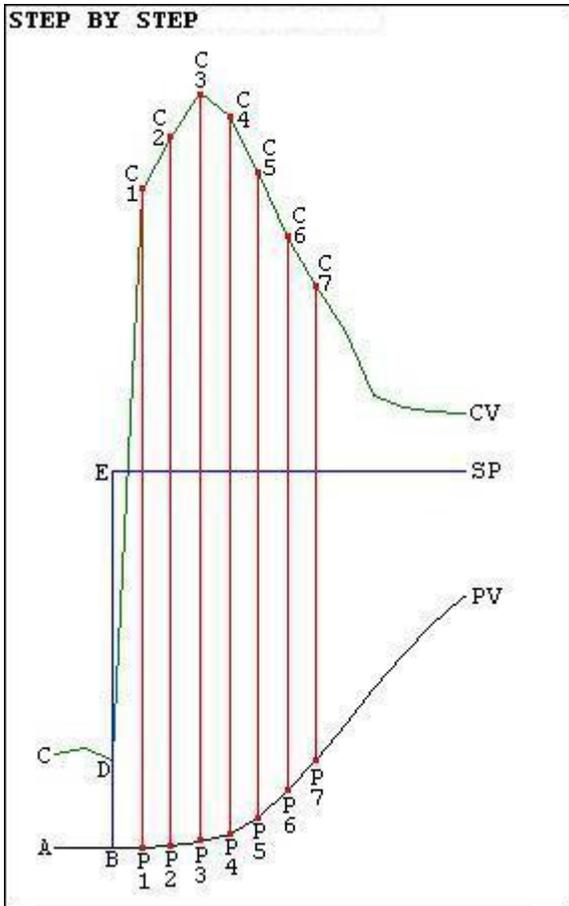to point D ... this is a very common form of test ...

now notice that at point J, the PV (Process Variable) had originally
settled down at a steady state of 109 degrees ... it maintained this same
temperature from point J up to point K ... and notice that the PV did not
even begin to respond for about 0.6 minutes AFTER the CV was stepped up
from 10% to 80% ... some people call this "flatline" period the system's
"lag" ... I (and many others) refer to it as the system's "deadtime" ...
and I'm sure that there are other names for it floating around out there
...

after it reached point K, the PV started to respond to the increased CV
drive ... the temperature really began to "take off" at point L ... this
particular point marks the temperature's maximum rate of change ...

suppose that a complete beginner happened to be watching the Ramrod system as it started heating up (as shown in Figure 6) ... if he didn't know any better, then he could easily assume that the rapid change of temperature shown from point K to point L might actually continue on for quite some time ... incidentally, this rate of change calculates out to be about 48 degrees per minute ... if that rate of increase continued on unchanged, it would trace the straight line shown from point L to point X ... then the temperature would go "off the charts" (above 500 degrees) ... well, a beginner might be confused by that "possibility" ... but we know that it just won't happen that way ... remember that we covered the reason why the temperature won't just "keep right on climbing" when we discussed the physics involved in Figure 3 ...

so the truth of the matter is that after that initial "rapid rise" from point K to point L, the rate of the temperature rise starts to "fall off" and eventually levels out at a new steady state value of 348 degrees at point M ... notice that I didn't say that the TEMPERATURE falls off ... rather it's the RATE OF THE TEMPERATURE RISE which is falling off ... specifically, the temperature is still rising – it's just not rising quite as fast ...

now we've finally got the foundation laid and we're almost ready to start examining the PID's Proportional action in detail ... but first we really need to "review" the step-by-step execution of the PID control as used in a PLC ...

STEP BY STEP

let's begin discussing this figure by looking at what is happening between point A and point B ... between point A and point B the PV (black) is tracking along right on top of the SP (blue) ... in other words, here the PID is giving perfect control of the process ... and if we take a look at the CV (green) during this particular period, we'll see that it's happily simmering right along from point C to point D ... the sun is shining ... the birds are singing ... life is lovely ...

and then, just as the PV is reaching point B, the operator decides to crank the SP up a notch ... you can see the SP move instantly from point B right straight up to point E ... now let's take a careful step-by-step look at what happens next ...

time is marching on ... and eventually we reach the time of the PID's next "tick" ... and now when the PID is triggered into execution, it sees the PV (its input) just as it reaches point P1 ... notice that the PV is still simmering along from point B to point P1 without ANY change in its value ...

when triggered into operation at point P1, the PID faithfully does its math calculations and finds out that the PV is now suddenly quite a bit "off target" from the SP ... and based on the present value of the SP and the present value of the PV, the PID calculates a new value for the CV ... and based on that new value, the CV is increased from point D right up to point C1 ...

and time is still marching on ... eventually we reach the time of the PID's next "tick" just as the PV reaches point P2 ... and if we look very closely, this time we might notice just a very slight increase in the value of the PV ... this rise in the PV is due to the recent increase in the CV ... that increase in the CV (output) is forcing the PV (input) to move toward the desired SP (target) ...

and now when the PID is triggered into operation at point P2, it does its math calculations again and comes up with another new value for the CV ... and based on that new value, the CV is increased again ... this time from point C1 up to point C2 ...

and time is still marching on ... eventually the PID "ticks" again just as the PV reaches point P3 ... and this time we notice a little bit more increase in the value of the PV ... the increased CV is still forcing the PV to keep moving toward the SP ...

and when the PID is triggered into operation at point P3, it comes up with another new value for the CV ... and the CV is increased again ... this time from point C2 up to point C3 ...

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and just once more for good measure ... time is still marching on ...
eventually the PID "ticks" again just as the PV reaches point P4 ... and
this time we notice even more of an increase in the value of the PV ...
the increased CV is still forcing the PV to keep moving toward the SP and
by now the PV has finally started making a substantial amount of change
from one tick to the next ...

and as before, when the PID is triggered into operation at point P4, it
comes up with another new value for the CV ... BUT ... this time the CV is
not increased ... instead it is decreased in value from point C3 down to
point C4 ...

even though this discussion focuses on the Proportional action, for
completeness I'll just briefly mention the Integral action here ... note
that the sudden jump in the CV from point D to point C1 was caused almost
totally by the PID's Proportional action ... the Proportional action (as
we'll soon cover) reacts only to the "amount of error" (how far the PV
happens to be from the SP) ... this "amount of error" suddenly increased
when the operator kicked the SP straight up from point B to point E ...
and once the Proportional action had "done its thing", then the Integral
action was responsible for the slow but steady increase of the CV from
point C1 to point C2 and on to point C3 ... the Integral action (as
discussed in another paper) reacts to the "amount of error over time" ...
notice that after its original jump, the "error" (the distance of the PV
from the SP) did not increase again during the period of time between
point B and point P3 (actually the "error" decreased during this period as
the PV slightly approached the SP) ... but the Integral action monitors
not only the "amount-of-error" but also the "amount-of-time-that-the-
error-has-existed" ... and that's how the Integral action contributed the
slow steady increase of the CV from point C1 - to point C2 - to point C3
...

possibly the most important thing involved in the little "review" that
we've just had is the basic idea of how the PID executes ONLY at these
little "tick – tick – tick" points in time ... specifically, when we (as
humans) look at a trend graph, we invariably focus on the shapes and
patterns of the little squiggly lines ... the PID doesn't look at the
process in the same way ... the PID bases everything that it knows, and
everything that it does, on these quick little "snapshots" of the data
that it sees whenever it is "triggered" into executing ... once the
technician comes to grips with this reality, it usually becomes a lot
easier to understand "what-the-PID-is-doing" and "why-the-PID-is-doing-it"
and "how-to-fix-it" when the PID doesn't work to suit us ...

now let's set up a PID instruction and see how it reacts when we try to
use "Proportional only" control for our Ramrod heating system ...

FIGURE 7   P = 0.00 TO 1.00

500

200°

E   25%

E   126°

75%   15%

0

22 mins.
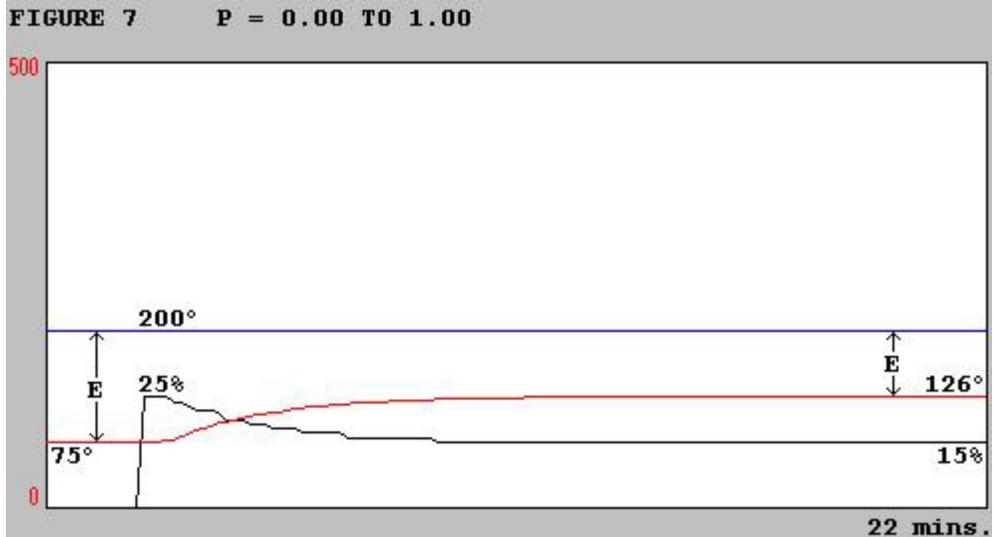
in Figure 7 the PID's Setpoint (blue trace) has been set for a target of 200 degrees ... to keep things as close to "apples-to-apples" as possible, we'll keep that same setting throughout this entire discussion ... also, the PID's Integral and Derivative actions will always be turned off throughout these tests ...

as the test shown in Figure 7 begins, the Proportional action has been given a setting of 0.00 ... in other words, the Proportional action has been turned OFF completely ... specifically, the Ramrod has NOT been heating and so the temperature has settled down at a steady state of 75 degrees – room temperature ... under these conditions the PID will calculate an Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided by 500 equals 0.25) ... soon after the test begins, we manually increase the PID's Proportional setting from 0.00 to 1.00 ... this causes a sudden jump in the CV ... the size of this jump is determined by two things: (1) the size of the Error, and (2) the setting of the PID's Proportional action ... in the case shown at the beginning of Figure 7, the Error has already been calculated to be 25% ... multiplying this by the Proportional setting of 1.00 results in a CV of 25% drive to the heater (0.25 multiplied by 1.00 equals 0.25) ... the results of this calculation are shown in Figure 7 by the CV as it instantly jumps up from 0% up to 25% ...

this new CV causes the Ramrod to begin heating ... as soon as the "deadtime" has elapsed, the PV starts to increase ... and that brings us to the "Catch 22" of Proportional-only control ... since the Proportional action is based on the size of the Error (the deviation from the target) we run into a big problem as soon as the PV heads toward the target ... specifically, as the PV approaches the Setpoint, the Error decreases (that's a good thing) ... but as the Error decreases, the Proportional action also decreases ... so the CV has less "drive" available to push the PV closer to the Setpoint (and that's a bad thing) ...

this "it-keeps-losing-steam" effect of Proportional-only control really confuses many beginners ... specifically, they usually ask: "but if the PV is still below the Setpoint, then why doesn't the Proportional action just drive the CV harder in an effort to put the PV on the target?" ... working through the math for the conditions at the end of Figure 7 should help us answer that question ... and keep in mind that the PID is NOTHING but math ...

for the test conditions at the end of Figure 7 notice that the Setpoint is still 200 degrees ... the PV has reached a temperature of 126 degrees ... so the PID calculates an Error of 15% (200 minus 126 equals 74 ... 74 divided by 500 equals 0.15) ... the PID then multiplies the Error by the Proportional setting to calculate the Proportional action as 15% (0.15 multiplied by 1.00 equals 0.15) ... and the sad truth is that a CV of 15% is simply not enough to push the PV any higher than 126 degrees ...

some beginners work through this and STILL have a problem understanding why the Proportional-only controller won't work ... they often wonder: "well, the CV increased ... and the temperature went up ... but why didn't it KEEP going up until it reached the Setpoint?" ... the answer to that question goes back to the concepts we covered in Figure 3 ...

remember that while we're trying to heat our system, it's as though there is an invisible "LOAD" which is always working against us ... and this load does NOT remain constant ... instead it increases in strength as the difference in temperature between the Ramrod and the room air increases ... at some definite point, the amount of heat LEAVING the Ramrod exactly balances the amount of heat ENTERING the Ramrod ... and for the settings used in Figure 7, that definite point is reached at 126 degrees ... and we'll have a steady state condition at that point until something changes ...


FIGURE 8   P = 0.00 TO 2.00
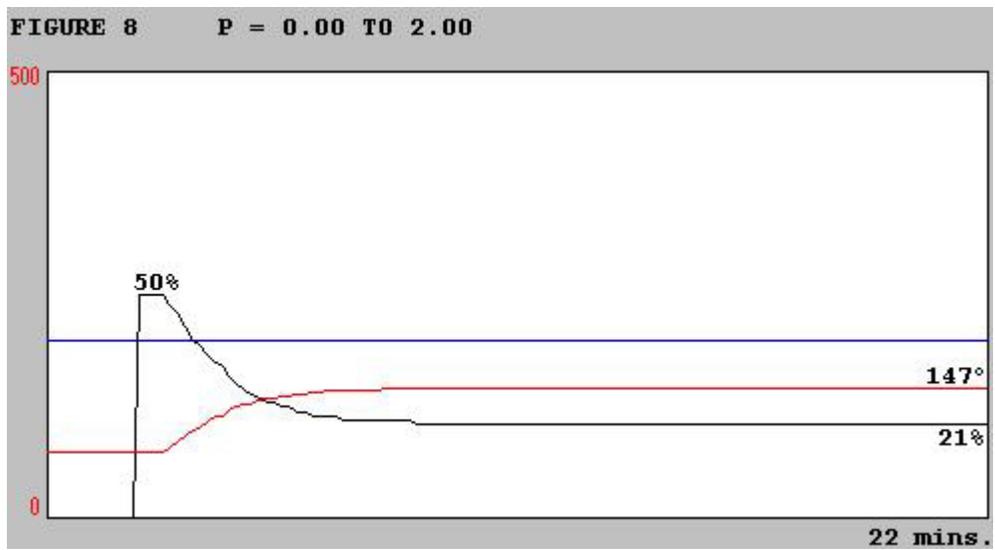
in Figure 8 we'll try using a higher Proportional setting ... maybe this will get us closer to the Setpoint ...

as the test shown in Figure 8 begins, the Proportional action has once again been turned OFF completely by a setting of 0.00 ... the PID will again calculate an Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided by 500 equals 0.25) ... soon after the test begins, we manually increase the PID's Proportional setting from 0.00 to 2.00 ... naturally this causes a sudden jump in the CV ... the size of this jump is determined by two things: (1) the size of the Error, and (2) the setting of the PID's Proportional action ... in the case shown at the beginning of Figure 8, the Error has already been calculated to be 25% ... multiplying this by the Proportional setting of 2.00 results in a CV of 50% drive to the heater (0.25 multiplied by 2.00 equals 0.50) ... the results of this calculation are shown in Figure 8 by the CV as it instantly jumps up from 0% up to 50% ...

this new CV causes the Ramrod to begin heating and soon the PV starts to increase ... but as the PV approaches the Setpoint, the decrease in Error causes a decrease in the Proportional action ... and so the CV has less "drive" available to raise the PV closer to the Setpoint ...

for the test conditions at the end of Figure 8 the PV has reached a temperature of 147 degrees ... so the PID calculates an Error of about 11% (200 minus 147 equals 53 ... 53 divided by 500 equals 0.106) ... the PID then multiplies the Error by the Proportional setting to calculate the Proportional action as 21% (0.106 multiplied by 2.00 equals 0.212)

so the 2.00 Proportional setting of Figure 8 gets us closer than the 1.00 setting of Figure 7 ... but still "no cigar" ... let's try doubling it again ...
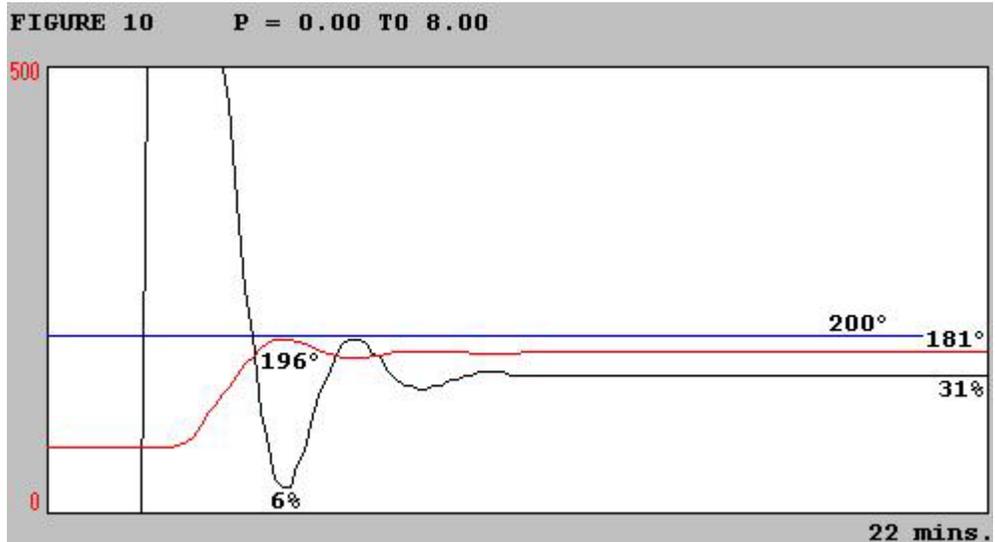

FIGURE 9   P = 0.00 TO 4.00
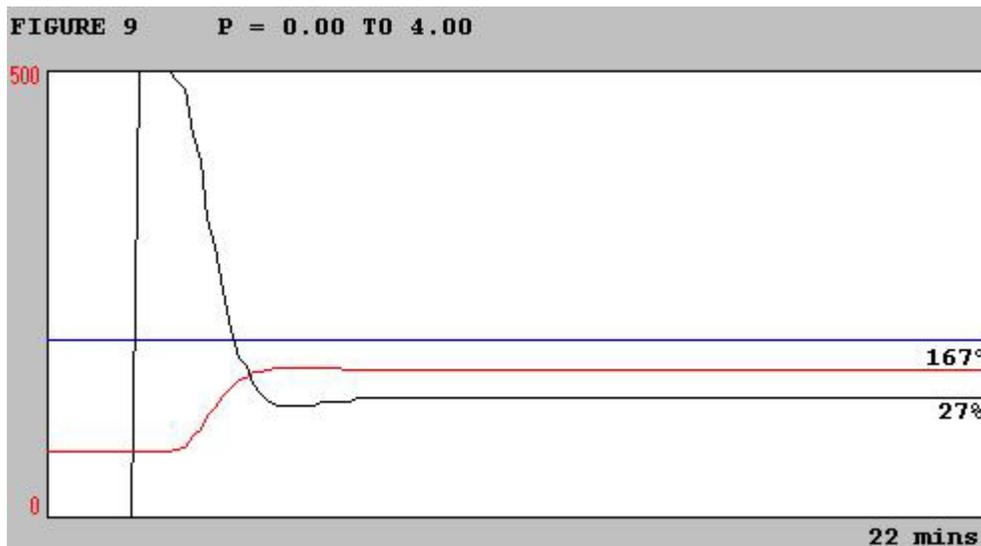
as the test in Figure 9 begins, the Proportional action has been turned OFF completely by a setting of 0.00 ... the PID will again calculate an Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided by 500 equals 0.25) ... soon after the test begins, we manually increase the PID's Proportional setting from 0.00 to 4.00 ... the size of the CV jump is always determined by two things: (1) the size of the Error, and (2) the setting of the PID's Proportional action ... in the case shown at the beginning of Figure 9, the Error has already been calculated to be 25% ... multiplying this by the Proportional setting of 4.00 results in a CV of 100% drive to the heater (0.25 multiplied by 4.00 equals 1.00) ... the results of this calculation are shown in Figure 9 by the CV as it instantly jumps up from 0% up to a fully on condition of 100% ...

as this new CV causes the Ramrod to begin heating, the PV approaches the Setpoint and the decrease in Error causes a decrease in the Proportional action ...

for the test conditions at the end of Figure 9 the PV has reached a temperature of 167 degrees ... so the PID calculates an Error of about 7% (200 minus 167 equals 33 ... 33 divided by 500 equals 0.066) ... the PID then multiplies the Error by the Proportional setting to calculate the Proportional action as about 27% (0.066 multiplied by 4.00 equals about 0.264 ... some discrepancy due to round-off is to be expected) ...

so the 4.00 Proportional setting of Figure 9 gets us closer than the 2.00
setting of Figure 8 but we're still not "home free" ... let's try doubling
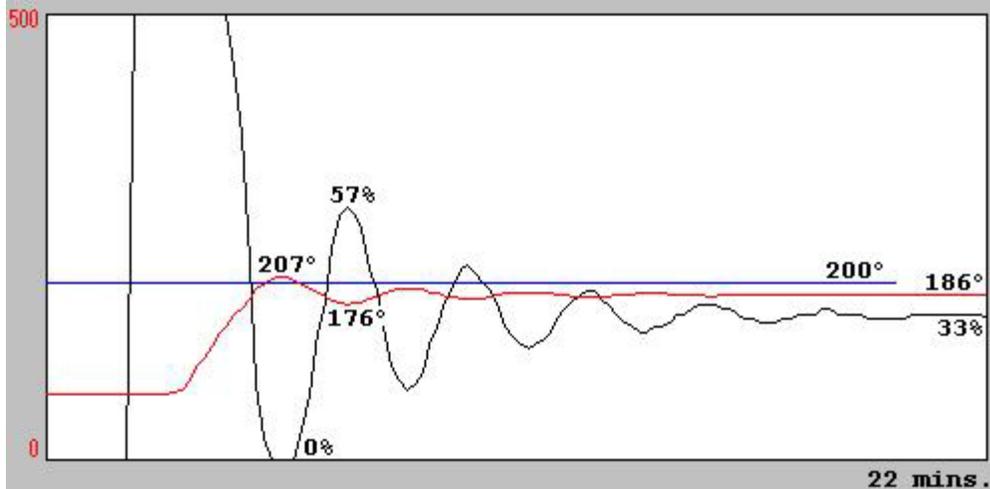it again ...

FIGURE 10   P = 0.00 TO 8.00

as the test in Figure 10 begins, the Proportional action has been turned
OFF completely by a setting of 0.00 ... the PID will again calculate an
Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided
by 500 equals 0.25) ... soon after the test begins, we manually increase
the PID's Proportional setting from 0.00 to 8.00 ... the Error has already
been calculated to be 25% ... multiplying this by the Proportional setting
of 8.00 results in a CV of 100% drive to the heater (0.25 multiplied by
8.00 equals 2.00) ... so actually the Proportional action would be 200% -
but naturally the CV can't go any higher than fully on – or 100% ... the
results of this are shown in Figure 10 by the CV as it instantly jumps up
from 0% up to a fully on condition of 100% ... and incidentally, if you
compare the traces of Figure 10 and Figure 9, you'll see that the
increased setting used in Figure 10 kept the CV at 100% for a longer
period of time ...

as the new CV causes the Ramrod to begin heating, the PV approaches the
Setpoint and the decrease in Error causes a decrease in the Proportional
action ... and this time we see just a little bit of oscillation starting
to take place ... that's because the longer time that the CV spent at 100%
allowed the PV to keep increasing for a longer period of time ... it got
as far up as 196 degrees before it started to fall off again ... at this
point the PID calculated a CV of about 6% (200 minus 196 equals 4 ... 4
divided by 500 equals 0.008 ... 0.008 multiplied by 8.00 equals 0.064 ...
about 6%) ... like I said earlier, the PID is NOTHING but math ...

for the test conditions at the end of Figure 10 the PV has reached a
temperature of 181 degrees ... so the PID calculates a CV of about 31%
(200 minus 181 equals 19 ... 19 divided by 500 equals 0.038 ... 0.038
multiplied by 8.00 equals 0.304 ... or about 31% with allowance for round-
off) ...

so the 8.00 Proportional setting of Figure 10 has us almost there – but
not quite ... this time let's increase it to 12.00 and try again ...
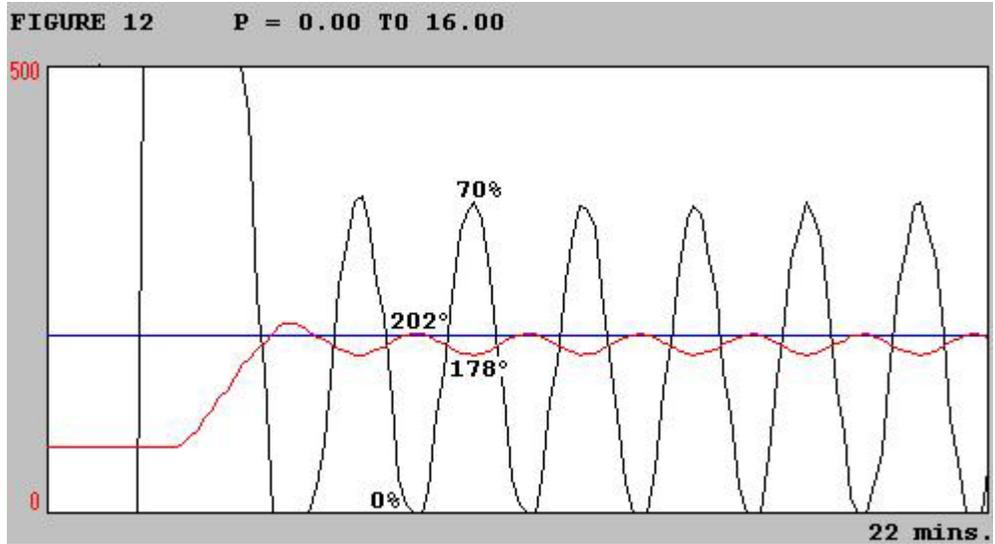
FIGURE 11   P = 0.00 TO 12.00

as the test in Figure 11 begins, the Proportional action has been turned
OFF completely by a setting of 0.00 ... the PID will again calculate an
Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided
by 500 equals 0.25) ... soon after the test begins, we manually increase
the PID's Proportional setting from 0.00 to 12.00 ... the Error has
already been calculated to be 25% ... multiplying this by the Proportional
setting of 12.00 results in a CV of 100% drive to the heater (0.25
multiplied by 12.00 equals 3.00) ... so actually the Proportional action
would be 300% - but naturally the CV can't go any higher than fully on –
or 100% ... the results of this are shown in Figure 11 by the CV as it
instantly jumps up from 0% up to a fully on condition of 100% ... and
incidentally, comparing the traces of Figure 11 and Figure 10 shows that
the increased setting used in Figure 11 kept the CV at 100% for a longer
period of time ...

as the new CV causes the Ramrod to begin heating, the PV approaches the
Setpoint and the decrease in Error causes a decrease in the Proportional
action ... and this time we see some serious oscillations that take most
of the 22 minute graph to finally die out ... that's because the longer
time that the CV spent at 100% allowed the PV to keep increasing for a
longer period of time ... this time it got up as far as 207 degrees (past
the Setpoint) before it started to fall off again ... at this point the
PID calculated a CV of about 0% (200 minus 207 equals -7 ... -7 divided by
500 equals -0.014 ... -0.014 multiplied by 12.00 equals -0.168 ... about -
2%) ... naturally the CV can't go any lower than fully off at 0% ... but
the math is still perfectly valid ...

and while we're here, let's run through the math on that next wave of the
oscillations ... the PV drops to a temperature of 176 degrees ... so the
PID calculates a CV of about 57% (200 minus 176 equals 24 ... 24 divided
by 500 equals 0.048 ... 0.048 multiplied by 12.00 equals 0.576 ... or
about 57% with allowance for round-off) ... by spending some time and
thought on this particular exercise, you can start to develop a "feel" for
what causes such oscillations to form ... and what causes them to
eventually die out ...

for the test conditions at the end of Figure 11 the PV has reached a
temperature of 186 degrees ... so the PID calculates a CV of about 33%
(200 minus 186 equals 14 ... 14 divided by 500 equals 0.028 ... 0.028
multiplied by 12.00 equals 0.336 ... or about 33% with allowance for
round-off) ...

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so the 12.00 Proportional setting of Figure 11 gets us just a little bit
closer to where we want to be ... but now we're starting to see some
serious oscillations at these higher settings ... oh, what the heck ...
let's go ahead and increase it up to 16.00 and just see what happens ...

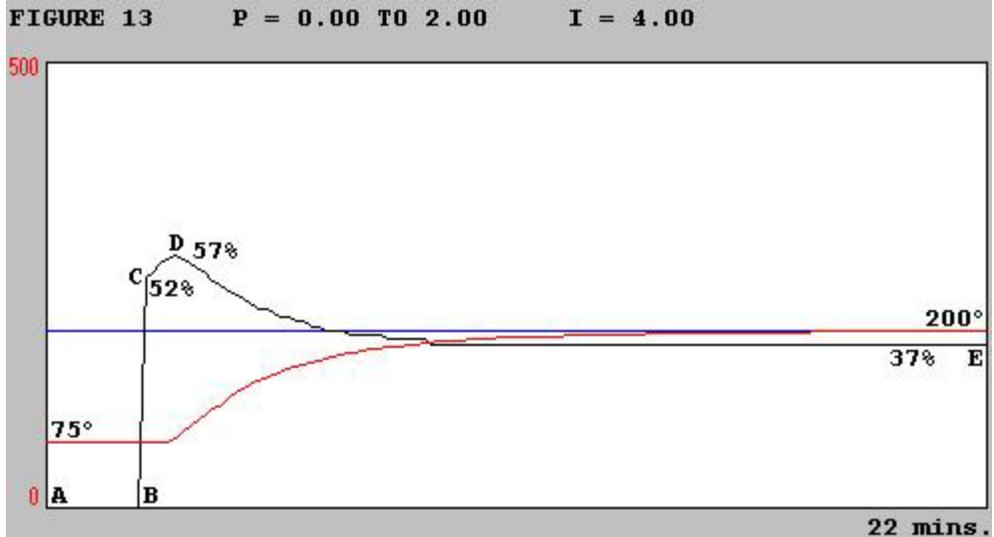FIGURE 12   P = 0.00 TO 16.00

as the test in Figure 12 begins, the Proportional action has been turned
OFF completely by a setting of 0.00 ... the PID will again calculate an
Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided
by 500 equals 0.25) ... soon after the test begins, we manually increase
the PID's Proportional setting from 0.00 to 16.00 ... multiplying the
Error by the Proportional setting of 16.00 results in a CV of 100% drive
to the heater (0.25 multiplied by 16.00 equals 4.00) ... so actually the
Proportional action would be 400% – but naturally the CV can't go any
higher than fully on – or 100% ... the results of this are shown in Figure
12 by the CV as it instantly jumps up from 0% up to a fully on condition
of 100% ...

as the new CV causes the Ramrod to begin heating, the PV approaches the
Setpoint and the decrease in Error causes a decrease in the Proportional
action ... and this time we see some intense sustained oscillations that
NEVER die out ... now the PV continuously oscillates between a maximum of
202 degrees and a minimum of 178 degrees ... when you get right down to
it, this isn't too much better than the simple on/off control that we saw
back in Figure 5 ...

just for completeness, let's run through the math on a least one wave of
the oscillations ... the PV drops to a temperature of 178 degrees ... so
the PID calculates a CV of about 70% (200 minus 178 equals 22 ... 22
divided by 500 equals 0.044 ... 0.044 multiplied by 16.00 equals 0.704 ...
or about 70%) ... these continuous peaks in the CV of 70% are causing the
oscillations which will never die out ... we've obviously pushed the
"Proportional-only" idea too far ...

and this series of posts confirms one of the "textbook" demonstrations of
"Proportional-only" control ... specifically, before you can add enough
Proportional action to get the PV all the way to the target, the system
goes into continuous oscillations ...
and finally (at least for now) ... for those of you who wouldn't be able
to sleep tonight from worrying about our "untuned" Ramrod ...

FIGURE 13   P = 0.00 TO 2.00   I = 4.00

in Figure 13 we've given up on the idea of using "Proportional-only" control for the Ramrod and dialed in a little bit of Integral action to our PID tuning ... and just so that we can continue comparing "apples-to-apples", we'll keep exactly the same test conditions as before ...

as the test in Figure 13 begins, the Proportional action has been turned OFF completely by a setting of 0.00 ... it's important to know that by setting the Proportional action to 0.00, we've also turned off the Integral action too ... that's because the Integral action (and the Derivative too) is multiplied by the Proportional setting ... so even though we're starting out with an Integral setting of 4.00 (minutes per repeat), the Integral can NOT affect the operation of the system during the beginning of the test ... (note that zero times anything is still zero) ...

and so as the test begins, the PID will calculate an Error signal of 25% of full scale (200 minus 75 equals 125 ... 125 divided by 500 equals 0.25) ... soon after the test begins, we manually increase the PID's Proportional setting from 0.00 to 2.00 ... multiplying the Error by the Proportional setting of 2.00 results in a Proportional "contribution" to the CV of 50% drive to the heater (0.25 multiplied by 2.00 equals 0.50) ... but ... the Integral action also makes its own "contribution" to the CV ... and that's what accounts for the extra "kick" which raises the CV up to 52% drive at point C ...

(note that it would be a good idea to eventually go back to Figure 8 and compare the CV trace of that test with the trace that we have here in Figure 13 ... be sure to notice that the only differences between the results of these two tests are caused by the addition of the Integral action here in Figure 13) ...
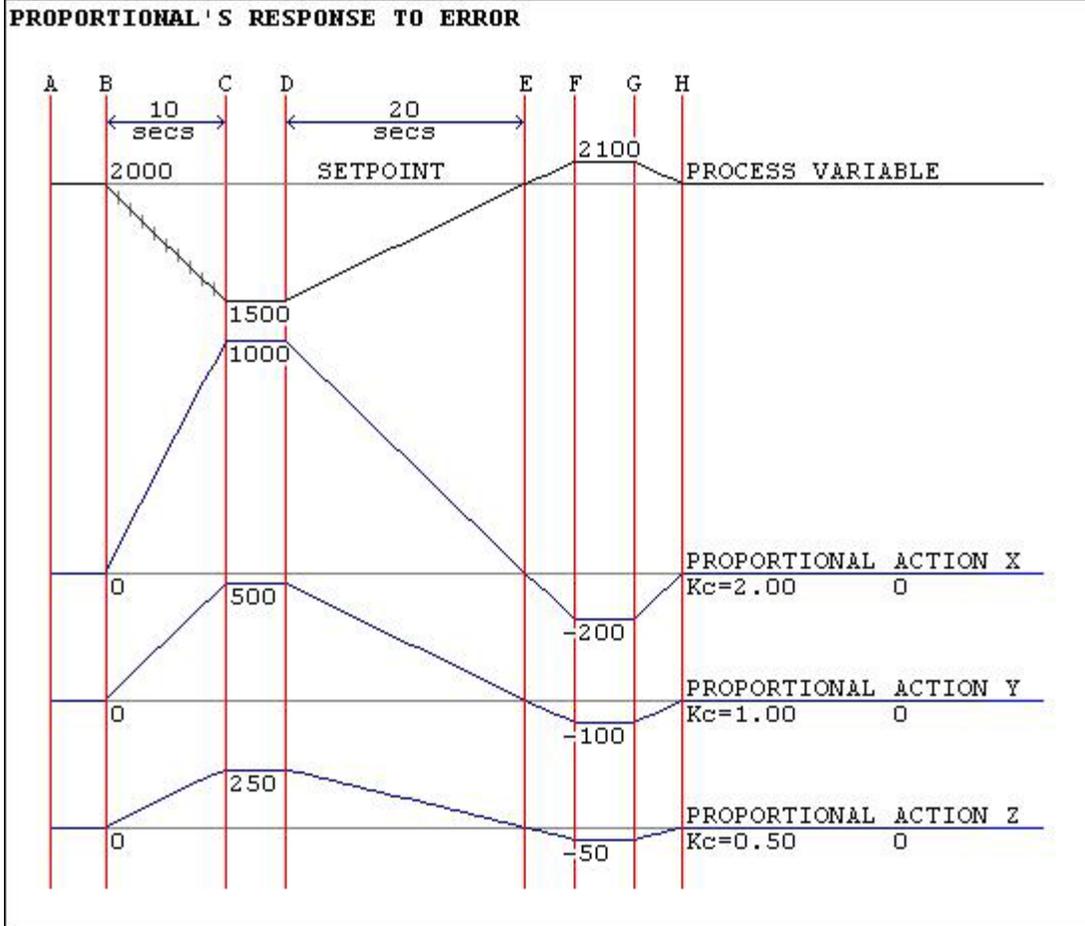
continuing on ... so at the start of the test, the Integral gives us a little bit of extra kick to get the PV headed in the right direction ... but that's not its most important benefit ... be sure to notice the gradual increase to the CV that occurs from point C to point D ... this "ramping up" effect is a direct result of the Integral action ... (note that the CV had a "flatline" response during the same period in Figure 8) ... so the Integral action is constantly working along with the Proportional action in trying to push the PV onto our Setpoint (target) ... and it's this constant contribution from the Integral action which

eventually keeps the CV simmering along at 37% when it reaches point E ... and the PV is right on target at 200 degrees ...

a thing of beauty is a joy forever ...

finally ... if you've fully understood the preceding discussion, then this next figure is probably a waste of time ... I'm including it here just for the people who might benefit from a side-by-side comparison of how changes to the PID's Proportional setting (Kc) can affect the amount of Proportional response ...

the top trace (black) in the figure below shows an artificial PV (input) signal that we'll use for discussion purposes ... the basic idea is that if we feed this exact same input signal into our PID over and over again, then we can use slightly different adjustments for our PID tuning values each time ... we can then compare "apples-to-apples" by examining any differences in the PID's output from one experiment to the next ... just keep in mind that the "profile" of the PV signal is NOT responding to the PID's output ... specifically, this input is an artificially generated "test" signal that always "does the same thing" regardless of how the PID tries to control it ...

```
PROPORTIONAL'S RESPONSE TO ERROR

  A   B       C   D              E  F   G   H

      |← 10 →|       |← 20 →|
         secs           secs

      2000         SETPOINT        2100        PROCESS VARIABLE

              1500
              1000


                                            PROPORTIONAL ACTION X
        0     500                           Kc=2.00        0
                              -200

        0                                   PROPORTIONAL ACTION Y
                              -100          Kc=1.00        0

              250
        0                                   PROPORTIONAL ACTION Z
                         -50                Kc=0.50        0
```

the test starts out at point A with the PV perfectly tracking along the SP
line ... specifically, between point A and point B, the PID is giving us
perfect control of the process ... the SP is 2000 ... the PV is 2000 ...
the sun is shining ... the birds are singing ... life is lovely ...

note: the PID system in our example uses numbers which range in value from
0 to 4095 to represent the signals we're discussing ... to nail this down,
the value 2000 in this example represents a signal which is about 48.8% of
full scale ... (2000 divided by 4095 equals 0.488) ... if (for one
example) our process happened to be using a temperature transmitter scaled
from 0 to 500 degrees F. then our 2000 count signal would correspond to a
temperature of about 244 degrees (500 times 0.488 equals 244) ... for the
time being, don't worry too much about the numeric values shown on the
figure ... we'll get into the math later ... let's just look at the
patterns of the squiggly lines for now ...

back to our story ... now at point B something happens to the system which
sends the PV signal downward away from the SP ... maybe someone shoved
another load of cookies into the oven ... but regardless of whatever
caused the disturbance, the next time the PID "ticks" (is "triggered" into
execution) it will see an input signal which is no longer "right on
target" ... in other words, the PLC will see the deviation of the PV from
the SP as an "error" ... and that "error" will cause the PID to make a
change in the CV ... now you should already realize that any change in the
CV will be the result of a change in the Proportional action – and/or in
the Integral action – and/or in the Derivative action ... but the only one

of these three actions that we're interested in for this discussion will be the Proportional ... and now let's talk about those three examples of Proportional action labeled X, and Y, and Z ...

first notice that all three traces (X, Y, and Z) have exactly the same basic shape ... the only differences between them are the various maximum and minimum values which they reached as we ran through the test ... next notice that each one of the traces is a mirror image of the PV trace at the top of the figure ... specifically, when the PV goes UP then the Proportional action goes DOWN ... and vice versa ...

going a little bit further, the Kc setting of 1.00 of Trace Y gives an EXACT (size-by-size) mirror image of the PV trace ... specifically, the Kc setting of 1.00 sets up a one-to-one relationship between the PV (the input signal) and the PID controller's Proportional output ... this clearly demonstrates the "lever-based ratio" action that we discussed back in Figure 4 ... along the same lines, the size of Trace X is twice as large as the PV signal ... this is due to the Kc setting of 2.00 which sets up a one-to-two relationship between the PV and the PID controller's Proportional output ... specifically, the PV moves one notch and the Proportional response moves two notches ... and of course, the size of Trace Z is only one-half as large as the PV signal ... this is due to the Kc setting of 0.50 which sets up a one-to-one-half relationship between the PV and the PID controller's Proportional output ... specifically, the PV moves one notch and the Proportional response moves only one-half of a notch ...

I've had several students over the years who "just-didn't-get-it" with the whole PID subject UNTIL they saw a chart like this last figure ... for some people this is the "ding! – now I understand it!" bell-ringer that makes everything start to fall into place ... it's helped others in the past ... maybe it will help you too ... I offer it for what it's worth ...

and that's my explanation of Proportional action for today ...

best regards,
Ron